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Business Modeling and Software Design

15th International Symposium, BMSD 2025
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Boris Shishkov
Editor

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Preface

Everybody's talking about failures – personal failures, institutional failures, governmental failures, societal failures, energy-supply-related failures, values-related failures, migration-related failures, pandemic-related failures, "green-deal"-related failures, failures to guarantee peace on Earth, failures to punish criminals, but also about business failures, software failures, data-management-related failures, telecommunications-related failures, and so on. Those are the "troubled waters" of life to date and we need "bridges" to get by, as in the iconic song of Simon & Garfunkel (Bridge Over Troubled Water). On the one hand, one should not expect that if life is essentially problematic, software and information systems would be able to turn this around but on the other hand, even a small improvement combined with other small improvements could inspire positive changes. Said otherwise, technology cannot compensate for deep societal problems but we hope that societally relevant technical and technological improvements can make us happier and stronger, helping us in this way to go over the troubled waters of today. Narrowing this challenge particularly to business (enterprise) models and their valuable role concerning the generation of (software-related) technical solutions brings us together in the **BMSD Community** – **Business Modeling and Software Design**.

This book contains the *proceedings* of **BMSD 2025** (the 15th International Symposium on *Business Modeling and Software Design*), held in *Milan*, *Italy*, on *1–3 July 2025* (https://www.is-bmsd.org). *BMSD* is an annual event that brings together researchers and practitioners interested in enterprise modeling and its relation to software specification.

Since 2011, we have enjoyed **fourteen successful BMSD editions**. The first BMSD edition (**2011**) took place in **Sofia**, **Bulgaria**, and the theme of BMSD 2011 was: "Business Models and Advanced Software Systems." The second BMSD edition (**2012**) took place in **Geneva**, **Switzerland**, with the theme: "From Business Modeling to Service-Oriented Solutions." The third BMSD edition (**2013**) took place in **Noordwijkerhout**, **The Netherlands**, and the theme was: "Enterprise Engineering and Software Generation." The fourth BMSD edition (**2014**) took place in **Luxembourg**, **Grand Duchy of Luxembourg**, and the theme was: "Generic Business Modeling Patterns and Software Re-Use." The fifth BMSD edition (**2015**) took place in **Milan**, **Italy**, with the theme: "Toward Adaptable Information Systems." The sixth BMSD edition (**2016**) took place in **Rhodes**, **Greece**, and had as theme: "Integrating Data Analytics in Enterprise Modeling and Software Development." The seventh BMSD edition (**2017**) took place in **Barcelona**, **Spain**, and the theme was: "Modeling Viewpoints and Overall Consistency." The eighth BMSD edition (**2018**) took place in **Vienna**, **Austria**, with the theme: "Enterprise Engineering and Software Engineering - Processes and Systems for the Future." The ninth BMSD edition (**2019**) took place in **Lisbon**, **Portugal**, and the theme of BMSD 2019 was: "Reflecting Human Authority and Responsibility in Enterprise Models and Software Specifications". The tenth BMSD edition (**2020**) took place in **Berlin**, **Germany**, and the theme of BMSD 2020 was: "Towards Knowledge-Driven Enterprise Information Systems". The eleventh BMSD edition (**2021**) took place in

Sofia, Bulgaria (*We got back to where we once started!*), and the theme of BMSD 2021 was: "Towards Enterprises and Software that are Resilient Against Disruptive Events." The twelfth BMSD edition (**2022**) took place in **Fribourg**, **Switzerland**, with the theme: "Information Systems Engineering and Trust", and the thirteenth edition (**2023**) took place in **Utrecht**, **The Netherlands**, with the theme: "Incorporating Context Awareness in the Design of Information Systems." The fourteenth BMSD edition (**2024**) took place in **Luxembourg**, **Grand Duchy of Luxembourg** (*Back to Luxembourg after BMSD-Luxembourg-2014!*), and the theme was: "Towards Socially Responsible Information Systems." The current edition brings BMSD back to Milan (ten years after BMSD-Milan-2015). BMSD-Milan-2025 marks the **15th EVENT**, with the theme: "***INFORMATION SYSTEMS AND THE TROUBLED WATER OF CURRENT LIFE***."

We are proud to have attracted distinguished guests as keynote lecturers, who are renowned experts in their fields: **Bert de Brock**, *University of Groningen*, The Netherlands (2024), **Gilbert Fridgen**, *University of Luxembourg*, Grand Duchy of Luxembourg (2024), **Willem-Jan van den Heuvel**, *Tilburg University*, The Netherlands (2023), **Hans-Georg Fill**, *University of Fribourg*, Switzerland (2022), **Manfred Reichert**, *Ulm University*, Germany (2020), **Mathias Weske**, *HPI -University of Potsdam*, Germany (2020), **Jose Tribolet**, *IST - University of Lisbon*, Portugal (2019), **Jan Mendling**, *WU Vienna*, Austria (2018), **Roy Oberhauser**, *Aalen University*, Germany (2018), **Norbert Gronau**, *University of Potsdam*, Germany (2017 **and 2021**), **Oscar Pastor**, *Polytechnic University of Valencia*, Spain (2017), **Alexander Verbraeck**, *Delft University of Technology*, The Netherlands (2017 **and 2021**), **Paris Avgeriou**, *University of Groningen*, The Netherlands (2016), **Jan Juerjens**, *University of Koblenz-Landau*, Germany (2016), **Mathias Kirchmer**, *BPM-D*, USA (2016), **Marijn Janssen**, *Delft University of Technology*, The Netherlands (2015), **Barbara Pernici**, *Politecnico di Milano*, Italy (2015), **Hend*erik* Proper**, *Public Research Centre Henri Tudor*, Grand Duchy of Luxembourg (2014), **Roel Wieringa**, *University of Twente*, The Netherlands (2014 **and 2023**), **Kecheng Liu**, *University of Reading*, UK (2013), **Marco Aiello**, *University of Groningen*, The Netherlands (2013), **Leszek Maciaszek**, *Wroclaw University of Economics*, Poland (2013), **Jan L. G. Dietz**, *Delft University of Technology*, The Netherlands (2012), **Ivan Ivanov**, *SUNY Empire State College*, USA (2012), **Dimitri Konstantas**, *University of Geneva*, Switzerland (2012), **Marten van Sinderen**, *University of Twente*, The Netherlands (2012), **Mehmet Aksit**, *University of Twente*, The Netherlands (2011), **Dimitar Christozov**, *American University in Bulgaria – Blagoevgrad*, Bulgaria (2011), **Bart Nieuwenhuis**, *University of Twente*, The Netherlands (2011), and **Hermann Maurer**, *Graz University of Technology*, Austria (2011).

The high quality of the BMSD 2025 technical program is enhanced by a keynote lecture delivered by an outstanding Dutch scientist: **Marijn Janssen**, *Delft University of Technology* (the title of his lecture is: "Technology Governance: Moving Away from the IT-Department and Becoming Ubiquitous") – 10 years after his BMSD-Milan-2015 keynote lecture titled: "Architectural Governance and Organizational Performance". Next to that, the presence (physically or distantly) of former BMSD keynote lecturers is much appreciated: *Bert de Brock* (2024), *Roy Oberhauser* (2018), and *Mathias Kirchmer* (2016). The technical program is further enriched by a panel discussion (featured by the participation of some of the abovementioned outstanding scientists) and also by *other discussions* stimulating *community building* and facilitating possible *R&D project acquisition initiatives*. Those special activities are definitely contributing to maintaining the event's high quality and inspiring our steady and motivated Community.

The BMSD'25 Technical Program Committee consists of a Chair and more than one hundred members from more than thirty countries – all of them competent and enthusiastic representatives of prestigious organizations.

In organizing BMSD 2025, we have observed **highest ethical standards**: We guarantee *at least two reviews per submitted paper* (this assuming reviews of adequate quality), under the condition that the paper fulfills the BMSD'25 requirements. In assigning a paper for reviewing, it is our responsibility to *provide reviewers that have relevant expertise*. Sticking to a **double-blind review process**, we guarantee that a reviewer would not know who the authors of the reviewed paper are (we send anonymized versions of the papers to the reviewers) and an author would not know who has reviewed his/her paper. We require that a reviewer *respects the reviewed paper* and would not disclose (parts of) its content to third parties before the symposium (and also after the symposium in case the manuscript gets rejected). We *guarantee against conflict of interest* by not assigning papers for reviewing by reviewers who are immediate colleagues of any of the co-authors. In our decisions to accept / reject papers, we **guarantee against any discrimination based on age, gender, race, or religion**. As it concerns the EU data protection standards, **we stick to the GDPR requirements**.

We have demonstrated for a fifteenth consecutive year a high quality of papers. We are proud to have succeeded in establishing and maintaining (for many years already) a high scientific quality (as it concerns the symposium itself) and a stimulating collaborative atmosphere; also, our Community is inspired to share ideas and experiences.

As mentioned already, BMSD is essentially leaning toward **ENTERPRISE INFORMATION SYSTEMS (EIS)**, by considering the **MODELING OF ENTERPRISES AND BUSINESS PROCESSES** as a basis for **SPECIFYING SOFTWARE**. Further, in a broader context, BMSD 2025 addresses a large number of EIS-relevant areas and topics.

BMSD 2025 received 48 paper submissions from which 23 papers were selected for publication in the symposium proceedings. Of these papers, 9 were selected for a 30-minute oral presentation (full papers), leading to a **full-paper acceptance ratio of 19%** - an indication for our intention to preserve a high-quality forum for the next editions of the symposium. The BMSD 2025 authors come from: Austria, Brazil, Bulgaria, Denmark, Finland, Germany, Kazakhstan, Luxembourg, The Netherlands, and USA (listed alphabetically); that makes a total of 10 countries to justify a strong international presence. Three countries have been represented at all fifteen BMSD editions so far – **Bulgaria**, **Germany**, and **The Netherlands** – indicating a strong European influence.

Clustering the BMSD'25 papers has been inspiring, opening different perspectives with regard to the broad challenge of adequately specifying software based on enterprise modeling. (a) As it concerns the BMSD'25 Full Papers: some of them are directed towards CONTRACTS CONCEPTUALIZATION (touching upon THEORY OF THE FIRM) and CONTRACTS FOR DATA, while others are touching upon VIRTUAL REALITY (VR) in general, and in particular: VR FOR SOFTWARE SUPPLY CHAIN and VR FOR TEACHING BPMN (Business Process Model and

Notation); a paper addresses ACTIVITY DIAGRAMS while another paper considers PROCESS MINING/MODELING WITH ARTIFICIAL INTELLIGENCE (AI); other papers are touching upon AI as well, addressing in particular: AI FOR BUSINESS PROCESS MANAGEMENT, AI-SUPPORTED ENTITY MATCHING, and QUANTUM AI FOR BLOCKCHAIN. (b) As it concerns the BMSD'25 Short Papers: some of them are directed towards REQUIREMENTS including FUNCTIONAL REQUIREMENTS while others are touching upon the specification of ADAPTIVE INFORMATION SYSTEMS, in general, and in particular touching upon: REAL-TIME OPTIMIZATION and CONTEXT AWARENESS; a paper addresses the SEMANTICS OF ACTIVITY DIAGRAMS while another paper considers AUTOMATED IMAGE MEASUREMENTS interwoven in SOFTWARE ARCHITECTURES; some papers are directed to MULTIVARIATE DATA and NEURAL-NETWORKS-RELATED SOLUTIONS as well as to the EVALUATION OF INFORMATION AND DATA MODELS, while a paper addresses OPEN DATA PORTALS; some authors consider enterprise-modeling-related and software-specification/AI -related challenges, touching upon actual and interesting application domains, addressing in particular the PEER-TO-PEER-PLATFORMS-DRIVEN CREDIT ASSESSMENT, DIGITAL HEALTHCARE, e-LEARNING, and e-MARKETING, while a paper addresses REGULATORY COMPLIANCE and PUBLIC VALUES with regard to DRONES (Unmanned Aerial Vehicles).

BMSD 2025 was organized and sponsored by the *Interdisciplinary Institute for Collaboration and Research on Enterprise Systems and Technology* (*IICREST*), co-organized by the *Institute of Mathematics and Informatics (IMI) – Bulgarian Academy of Sciences*, and technically co-sponsored by *Cesuur B.V.* and *Scheer Americas Inc.* Cooperating organizations were *Aristotle University of Thessaloniki* (*AUTH*), *Delft University of Technology* (*TU Delft*), the *Dutch Research School for Information and Knowledge Systems* (*SIKS*), and *AMAKOTA Ltd*.

Organizing this interesting and successful symposium required the dedicated efforts of many people. First, we thank the *authors*, whose research and development achievements are recorded here. Next, the *Program Committee members* each deserve credit for the diligent and rigorous peer reviewing. Further, appreciating the Italian organizational support (we would especially mention Angelo Bellanova!), we would like to mention the excellent organization provided by the *IICREST team* (supported by its *logistics partner, AMAKOTA Ltd.*) – the team (words of gratitude to *Aglika Bogomilova*!) did all the necessary work for delivering a stimulating and productive event. We are grateful to *Coen Suurmond* and *Alexander Verbraeck* for their inspiring support with regard to the organization of BMSD 2025. We are also grateful to *Springer* for their willingness to publish the current proceedings and we would like to especially mention *Ralf Gerstner* and *Christine Reiss*, appreciating their professionalism and patience (regarding the preparation of the symposium proceedings). We are certainly grateful to our *keynote lecturer*, *Prof. Marijn Janssen*, for his inspiring contribution and for his taking the time to synthesize and deliver his talk.

We wish you inspiring reading! We look forward to meeting you next year in the beautiful *Greek* island of *Rhodes*, for the *16th International Symposium on Business*

Modeling and Software Design (*BMSD 2026*), details of which will be made available on: https://www.is-bmsd.org.

June 2025 Boris Shishkov

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Invited Speaker

Marijn Janssen	Delft University of Technology, The Netherlands

Abstract of Keynote Lecture

Technology Governance: Moving Away from the IT-Department and Becoming Ubiquitous

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Abstract. Technology often is traditionally managed by separate departments, which are loosely connected to the business departments. All kinds of IT governance frameworks have been developed for the department and interaction with the business department. As technology becomes ubiquitous and interwoven in every part of the organizations and even determines competitiveness, the technology governance needs to be changed as well. Due to the blending of business and IT, organizational and IT governance have become more interwoven and must be adapted. Although governance should limit what can be done with IT to ensure privacy and security, governance should enable ambidexterity by ensuring sufficient leeway for people to maneuver, experiment with, and introduce new technology. This delicate balance must be dealt with. Without that the risks of avoiding taking any steps or the desire to innovate will dominate.

Contents

Full Papers

A Business View on Information System Development

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Abstract. The paper presents a view on the development of a business information system that is firmly based on the theory of the firm and theories about business contracts. The common element in those theories is the notion that doing business is embedded in institutional and social structures. Hence, a business agreement cannot be reduced merely to a quantifiable exchange of goods, as the neoclassical economic view would have it. This means that information about business agreements involves much more than the order information represented in the IT system. It is about an understanding of background, commitments, expectations. Context and interpretation play an important role. Hence, development of a business information system cannot be reduced to IT systems only, other information channels have to be analysed and designed as well. Founded in business and legal theory, the paper argues against two kinds of distortion in developing information systems for business: distorting business processes by a reductionistic understanding of the nature of business agreements, and distortion of business information by reducing it to IT-processable data only.

Keywords: Business · Relational Contracts · Information System Development · Affordances

1 Introduction

In a business organisation, the question "What is a customer order?" will probably be answered by pointing to a customer order in the computer system. However, a customer order is much more than that: it is a mutual commitment of seller and buyer to deliver a performance in accordance with the general legal framework, the established patterns in the specific kind of market, the established relationship between the business partners, and the expectations raised by the communications between the business parties leading to the written contract. A healthy business relationship is about reliability and trust: do the business parties fulfil their mutual promises and commitments? Do they live up to the expectations? In business, the focus is on building a reputation in the market and legal enforceability is generally much less an issue.

In order to understand information system development for a business organisation, and in order to develop such a system successfully, it is important to be aware what business information is about and how it will support the business organisation. When

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the mindset is predominantly geared towards information represented in IT systems, it might miss many important aspects of business processes. As Sefanja Severin observed in his contribution to the BMSD symposium in 2024: "Over the past few decades, organizations have struggled to align business and IT to improve their performance. An important inhibitor of alignment is the lack of business understanding by IT" [1]. It is an example of colonisation of the institutional and social world of business by (hard) systems thinking, to borrow diagnosis and terminology from the combination of Habermas [2] and Checkland [3].

The contribution of this paper is to give a structured account of the role of different kinds of information in a business organisation, and to present some important consequences for the development of business information systems. The argument is based on a coherent set of theories about business, contract law, organisation, and information. The core common to all these theories could be characterised as non-deterministic, open, evolving, context-sensitive. This is as opposed to a common element found in many IT-centred approaches, focusing on deterministic behaviour based on rationalistic models of business processes. Or, in terms of often cited metaphors, this is the opposition between perceiving an organisation as an organism or as a machine [4].

The structure of the paper is as follows. First is a section about theories of the firm and relational contracts. The section after it shows how different kinds of information shape the fulfilment of business agreements in manufacturing companies, and how the concept of a business information system should cover the structuring of all kinds of information flows and not only be focusing on IT systems. Following a section with considerations about organisations, the concept of a business information system is defined, illustrated, and visualised. Next, implications of the business-based view on information systems for system development are discussed. In the conclusion the main line of argumentation is recapitulated, and it will be discussed what is required to broaden the argument for other types of business and also for public organisations.

2 Business, Business Agreements, Fulfilment

2.1 Theory of the Firm

The research presented in this paper is founded on the theories about business and business agreements originating with Coase, Kay and MacNeil. Ronald Coase introduced the concept of transaction costs involved in the preparing, concluding and enforcing of business agreements. Finding business partners, discussing agreements and ensuring a successful fulfilment of the agreements comes at a cost. Part of such costs is in the building of relationships with potential business partners. Another part is in discussing, concluding and enforcing actual business agreements, including the costs of internal legal and administrative support [5]. John Kay analysed what factors determine the success of a company, resulting in the concept of distinctive capabilities: "A capability can only be distinctive if it is derived from a characteristic which other firms lack" [6]. Further, such capabilities must be sustainable over time and appropriable to markets and products. In order to be distinctive over time, such capabilities must not be easily copied by competitors. In his book, Kay discussed architecture, reputation, innovation and strategic assets as primary sources of distinctive capabilities. For this paper, the first two are the most important. Reputation will be discussed below in the paragraph about relational contracts. About the value of architecture, Kay writes that it rests “in the capacity of organizations which establish it to create organizational knowledge and routines, to respond flexibly to changing circumstances, and to achieve easy and open exchanges of information. Each of these is capable of creating an asset for the firm – organizational knowledge which is more valuable than the sum of individual knowledge, flexibility, and responsiveness which extends to the institution as well as to its members” [6].

In later work, Kay analysed the different forms of uncertainty a company has to cope with, and applied the concept of radical uncertainty for developments that could not be meaningfully specified, let alone quantified. Dealing with radical uncertainty definitely qualifies as a distinctive capability, as it is highly dependent on the experience and insight of individuals as well as the way such knowledge is shared in the company (cf. the citation about architecture above) [7]. Arie de Geus’ work on scenario planning in a major multinational is an excellent example of long-term planning, dealing with a high amount of radical uncertainty [8].

MacNeil analysed the discrete contract as a paradigm of the transaction of neoclassical economics in which: “no relation exists between the parties apart from the simple exchange of goods”. In contrast, a relational contract “involves relations apart from the exchange of goods itself” [9]. Similarly, Austin-Baker and Zhou define relationalism as “the view that contracts are not one-off, discrete events, but involve sometimes complex and long-term relations, and have a variety of wider contexts in which they need to be viewed to be fully understood” [10]. For the purposes of this paper, the three main characteristics of relational contracts are the aspects of social habits and conventions, the role of trust and reliability, and the role of commitment in business agreements.

Apart from the inevitability of social relations in doing business, relational contracts have a clear economic advantage. It reduces transaction costs both by relying on trust in business relationships as well as by relying on enforceability by institutions. Hence, doing repeated business with trusted partners reduces transaction costs as long as the partners live up to trust invested in the business relation. Being viewed as a reliable (potential) business partner, knowledgeable and prepared to solve incidental problems, adds to the reputation of a firm (as discussed above, one of the grounds of distinctive capabilities).

All three authors reject the mainstream neoclassical economic theory about the functioning of markets as reductionistic. They asked fundamental questions about the presuppositions underlying that neoclassical view. They come up with answers and fundamental concepts based on an analysis of what is necessarily happening when doing business in our social and institutionalised world. Doing business is not free of costs, as the neoclassical economic view has it, but involves transactions costs [5]. Markets are not completely transparent and without history but constrained by institutions, social conventions and evolved patterns; business contracts concluded on those bounded markets are necessarily relational contracts [9]. Doing business is about finding and using opportunities where your firm has competitive advantages [6], and about concluding and fulfilling relational contracts [5, 8]. Your business processes are due to fulfil those agreements such that not only your written business commitments will be satisfied, but also that the (reasonable) expectations of your business partner are satisfied or even exceeded [6].

As Kay writes in his most recent work, doing business is not about a collection of one-off transactions on an anonymous, “relation-free” and “history-free” abstract market, neither is it about a static world repeating the same transactions with the same specifications over and over again, but: “adaptation with selection, the basic mechanism of evolution, is the process through which collective intelligence develops and the means by which successful firms find products and business processes appropriate to the needs of their customers. Disciplined pluralism, which allows freedom to experiment but is quick to end unsuccessful experiment, is inseparable from economic progress” [11]. Awareness of evolving business relationships in a dynamic environment is an important background for developing a business information system.

2.2 Business Agreements

In doing business, the outside-facing processes of the company are interacting with customers, suppliers, and various kinds of governmental and non-governmental institutions. Within the business organisation, the job of the primary processes is to fulfil the business agreements.

The first issue is, when a business agreement is closed, what did the business partners agree upon? That is: which results, actions, performances did each of them commit to, on which conditions and on which grounds? In the background, implicitly or explicitly referred to in individual orders, are specifications such as: product catalogue, framework contract, terms of sale, terms of purchase, terms of delivery. Also in the background, present but not referred to in individual orders, are tacit expectations about patterns and habits. They will be partly based on the nature of the market, partly based on general reputation in the market, and partly (if applicable) based on the history of the specific business relationship of the seller and buyer. This might also extend to the relationship on a personal level. The most visible part of the agreement is the specification of hard order data such as item codes, quality, price, delivery date. Additional commitments might be part of the agreement, such as requests, instructions and considerations (“unloading must be finished before 11:00am”, “delivery before 11:00 would be appreciated”, “order changes allowed until 24 h before delivery”, “delivery must be on H2 pallets, otherwise the shipment will be returned”, “please call when truck is on its way”, “make sure the truck is clean this time”). This kind of information is about promises, commitments and expectations. In such cases, a business party engages in a commitment to try to accommodate the wishes of the other party. Nuances matter: how strongly does a party commit to a wish? “I will give it a try” is quite different from “I cannot promise, but I will do my utmost”. Fulfilment of such aspects of the business agreement will mostly not be enforceable, but will have an impact on reputation and future business, circumstances considered.

2.3 Fulfilment of Business Agreements

From the business viewpoint the primary criteria for the successful fulfilment of business agreements are (1) the creation of value for the customer by satisfying the promises, commitments and expectations as agreed between the business parties and (2) the creation of value for the own firm by optimal utilisation of available resources. Of course, those two criteria might conflict, and the firm must find a trade-off between value for the business partner and value for the company itself. Also, there are many other institutional and societal background norms involved, partly based on written rules and partly based on convention and trust.

Creating value for the customer means delivering the right product with the right quality in the right quantity at the right time on the right place. In order fulfilment, execution of the primary processes is about delivering the product with the agreed properties required for satisfying the customer needs; while planning and coordination processes are about creating the right internal circumstances required for the right execution of the primary processes. The first kind is about what and how. The second kind is about where and when, and – equally important – about the supply of resources required for the smooth execution of the primary processes.

In the execution of its primary processes the company must see to it that the agreed commitments and expectations about the end product are met (the end product being according to specifications is part of it, but not always the whole story). In its planning processes the company must see to it that (1) agreed commitments and expectations about the timely delivery of the end product to the customer are met, and (2) that the company's available resources are used efficiently. Mutual adjustment between sales, production, logistics and planning are important to find solutions for conflicts between the creation of value for the customer and the company's capacities and efficiency. During actual execution the primary processes and their resources must be monitored – and possibly adjusted – in real time.

2.4 Business, Agreements, Fulfilment

Figure 1 shows three core elements of business: doing business, business agreements and fulfilling agreements. At the core of a business agreement is a specified exchange of goods and money (right side of Fig. 1). The way the exchange is executed is subject to commitments and expectations (left side of Fig. 1). For a satisfactory fulfilment of business agreements business processes must know about both sides of the business agreement. This includes knowledge about what counts as a satisfactory fulfilment of a business agreement regarding acceptable tolerances of quantities, substitutes, quality, dates and times. A general understanding of the own business is the background against which business processes are executed.

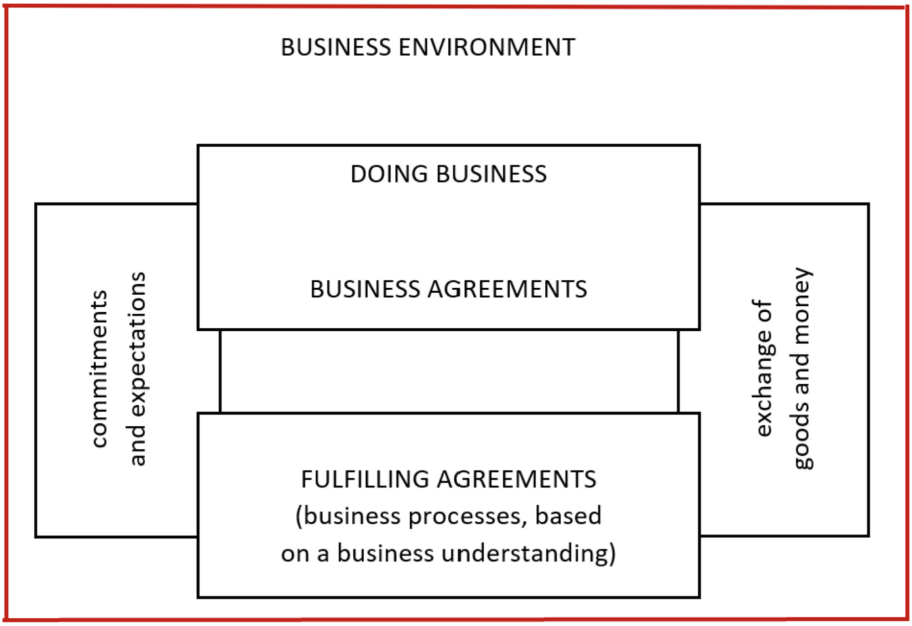

Fig. 1. Satisfactory fulfilment of business agreements is about the core transaction as well as accompanying commitments and expectations

3 Information and Business Processes

3.1 Information Shapes Behaviour

The concept of information is notoriously hard to define. In our view, information is related to action, it has meaning in connection with the (future) behaviour of an actor: information shapes action (cf. Checkland and Holwell [12]). In a human actor, information is interpreted against a background of knowledge and experience *in order to* reach some intended future state (Checkland and Holwell: 'purposeful behaviour'). Humans are accountable for their actions. In a computer, information is processed against a background of a previous state *which results in* a successor state. Computers are not accountable for their actions (an important, recurrent and often difficult question: who is accountable for computer actions?). The italics signal a fundamental difference in the way information is used by humans and in computers: human behaviour is governed by purposeful actions (information is interpreted for a purpose), computer actions are governed by causality (information processed by logical rules).

Information needs some material existence in order to be perceived or processed. That might be in the brain, in an IT system, or in physical signs in the external world. Prior to interpretation or processing, information must be produced. That can be consciously organised by purposeful human behaviour (think of human interpretation and actions in primary business processes, or in designing IT systems), or may be an unintended consequence of actions by humans, by computers, or by the laws of physics.

3.2 Kinds of Information in Business Processes

Background Information. Knowledge and experience, the background for human interpretation of information, are themselves the sediments of earlier digested information. Information about products and processes can also be found in handbooks and documentation (often in electronic form nowadays). Background information is partly developed by dedicated learning processes, and partly picked up in practical behaviour. Important as such background-forming processes are in an organisation (also for the moulding of the organisational culture: "this is the way things are getting done here in our company"), they will not be discussed here. However, what will be an issue is how such background information combines with actual information in processes. Think of the way people talk, the specific and sometimes idiosyncratic meaning of certain words, and the way references are used.

Kinds of Information. Generally speaking, **standardised information** will do the job for fulfilment of orders in the planning, coordination and execution of the primary processes as long as circumstances are beneficial. The customer order has a set of typical parameters such as customer, shipment address, invoice address, list of items and quantities. The specifications of their relevant properties (usually in some form of master data) in combination with background knowledge and experience will be sufficient information for doing the job and satisfying the customer needs and expectations.

In regular operation under normal circumstances, lots of **background information** is involved in the business processes. On the shop floor, in the execution of the primary processes, markings on floors and walls provide **physical information, marking routing and stocks** for material flows. Replenishment of working stock at the production lines is driven by a combination of seeing physical stocks on its location and planning information about expected consumption. Shop floor workers self-organise and easily adapt to circumstances, thereby optimising the utilisation of shop floor resources. Another form of **physical information on movable goods** (products and containers) is the use of labels, making them recognisable in physical space. It is easy to put on a screen that bin 3 4012345 123456789 5 must be fetched, it is hard to find that bin in physical stock based on such a reference only. Still another kind is **information about allowable deviations** from product specifications, from schedules and planned quantities of internal orders. How much overshoot or undershoot is tolerated, under which circumstances? When to consume the last quantity of available material, and when to return it to stock (at extra cost)? The aggregate of many such small decisions determines actual efficiency on the shop floor, and depend on the interpretation of experienced shop floor personnel of the combination of physical information, planning, circumstances, and applicable instructions and guidelines ('applicable' might in itself be a term subject to interpretation, as well as how to deal with contradictory instructions). In practice, shop floor workers will have a degree of local autonomy for such decisions, sometimes requiring mutual adjustment with prior and subsequent processes, in other cases requiring higher level decisions by planners and/or sales (which might be problematic at 3:00am). Part of the operational information required for the primary processes comes from the planning process. Additional information comes from daily or weekly meetings of shop floor managers, where specific incidents, issues and challenges are discussed resulting in specific instructions and guidelines for the next days.

Planning processes are based on **market information** about expected sales and **information about availability of resources** which is partly information about the capacity and lead times of suppliers to deliver the required resources. In regular operation planning decisions are often about trade-offs between customer value and value for the own company. **Close cooperation and regular meetings** between planning, sales, production and logistics provides the planners with actual information for making such trade-off decisions. This is a main mechanism along which information about commitments and expectations is shared. The major part of the output of planning is a set of internal orders, supplemented with additional points of awareness, instructions and guidelines when applicable.

4 Organisation

Generally speaking, the role of the organisation is to structure and stabilise business processes. Mintzberg defined the structure of an organisation as "the sum total of the ways in which it divides labor into distinct tasks and then achieves coordination among them" [13]. Different parts of the organisation are "joined together by different flows – of *authority*, of work *material*, of *information*, and of *decision processes* (themselves informational)" (italics in the original). An organisation has a system of formal authority (the hierarchical view on organisations) and has regulated flows. "Today, both views live on in the theories of bureaucracy and of planning and information systems" wrote Mintzberg back in 1979. It would be safe to state that the "regulated flow view" is still a leading paradigm of contemporary business information systems (as well as of concepts such as business process management and enterprise engineering). Minzberg also recognises the view on an organisation as 'a system of informal communication'. He cites work of Dalton from 1959 who defined formal or official as "that which is planned and agreed upon" and informal or unofficial as "the spontaneous and flexible ties among members, guided by feelings and personal interests indispensable for the operation of the formal but too fluid to be entirely contained by it.". Mintzberg adds: "Thus, whereas the first two views of the organization [authority and regulated flows] focus on the formal use of direct supervision and standardization, this one [informal and unofficial] focuses on mutual agreement as a coordination mechanism".

Between Dalton in 1959 and Mintzberg in 1979, Anthony published a book about planning and control systems. His analysis contains a highly rational approach to the "informal and unofficial" aspect of the actual work in organisations, which contrasts with Dalton's negative qualification "feelings and personal interests" (which surely exist, but are not the whole story!). What Anthony wrote about plans also applies to the design of organisational structures: "Since no one can foretell the future precisely – that is, since people are not clairvoyant – it follows that in some respects actual events will differ from the assumed events that the plans were designed to meet…. Top management wants middle management to react to the events that actually occur, not to those that might have occurred had the real world been kind enough to conform to the planning assumptions…. That is why our definition of management control is worded in terms of the effective and efficient utilization of resources, rather than conformance to plans" [14]. This approach is compatible with the metaphor of the organisation as organism adapting to a dynamic and not fully predictable environment [4], and also compatible with the theory of the firm presented above.

Taken together, this approach to the organisation acknowledges its hierarchy and regulated flows, but acknowledges also the important role for adaptive interaction based on ad hoc information should the need occur. In a dynamic environment, organisations must be able to cope with the unexpected (when needed, in unregulated, flexible, adaptive ways). It should be noted that the other side of the coin is that deviations are accounted for (which is again about authority and regulated flows). The general organisational behavioural rule 'comply or explain' gives operational freedom, and is also fully consistent with the principles of hierarchy and regulated flows. The implication for a business information system is that its registration functions must be able to register whatever actually happened, regardless what was planned or prepared.

4.1 Who is Acting?

In thinking about the role of IT systems in business organisations, it is important to remember that such systems are instruments, not actors. It is certainly not necessary that the IT system must be able to cope with each and every scenario possibly occurring in business processes. In the question "how do you want the system to react to the following situation in your business process?" this aspect is missing. It leads to an IT-centred focus where scenarios are described, applicable rules for the scenarios are discussed, and those are the rules that will determine the behaviour of the IT-system-to-be. In this approach, the IT-system is viewed as the main actor in the business process, and it must have the capability to deal with all possible scenarios. As a consequence of this view, people in processes are analysed in relation to the system as a kind of 'peripheral devices' to the IT system (as suggested by the designation "user"). Moreover, this view might be shared with managers who like to view their organisation as a machinery, and people as potential unruly sources of disturbance (metaphor of the organisation as machine).

In the business-centred view discussed in this paper, the IT system is not an actor in its own right but it is an instrument. People would be the main actors in the business processes, being able to understand the business and business agreements, and acting accordingly in interpreting the business context (often routine with only normal variability, sometimes with special demands due to agreements or context, and sometime disruptive due to actions or breakdowns). The question is then: "how do you want your business process to deal with the following scenario, what is the role of your personnel in realising that desired behaviour, and how would your personnel be supported by the information system-to-be?".

4.2 Affordances

Related to the concept of actors is Gibson's concept of affordances: "the affordances of the environment are what it offers to the animal, what it provides or furnishes, either for good or ill" [15]. Gibson emphasises the complementarity of the animal and the environment. Depending on the physical, physiological and mental properties and capabilities of the animal, the same environment can offer different affordances to different animals. Or, to translate this into a business environment, a computer screen densely populated with information provides the expert planner a quick overview of the situation, but would provide confusion to a novice planner because of the excessive amount of information. It is fruitful to describe the mutual relations in terms of affordances:

1. Business processes provide affordances for doing business with customers and suppliers; hence the goal of process design is the creation of the "right" affordances
2. Information systems provide affordances for business processes; hence the goal of information system development is the creation of the "right" affordances for the business processes
3. Business should be free to use the affordances of the business processes creatively (while it is a duty of the internal organisation to make clear the real costs of fulfilment of non-standard orders to business people)
4. In business processes, personnel should be able to use the affordances of the information system freely and creatively (while it is a job for the internal controlling mechanisms to make clear when and why a non-standard interpretation of information was used).

In other words, the design of business processes and their information systems should not just focus on the execution of concrete actual and future scenarios. Design is about creating possibilities, grounded in the combination of a sense of reality (actual and desired scenarios) and a sense of possibility (creating space for alternative use of affordances). The flexibility of a business organisation to evolve in interaction with its evolving environment is an important aspect for business. Of course both reliability and efficiency require standardisation and repetition, which are design goals of processes. At the same time, the business organisation must be able to absorb incidental and unforeseen irregularities as well as adapt to shifting circumstances. Therefore, it is not right to think about the design of business processes as frozen in time, part of the design should be robustness (the capability to absorb irregularities in existing processes) and adaptability (the capability to evolve and adapt the structure of processes).

5 (Business) Information System

5.1 Information System

The OED gives as the general meaning of **system**: "A set or assemblage of things connected, associated, or interdependent, so as to form a complex unity; a whole composed of parts in orderly arrangement according to some scheme or plan" [16]. For a **business information system**, a slightly modified version of Bocij's definition is in harmony with the analysis in this paper: "a group of interrelated components that work collectively to carry out input, processing, output, storage and control actions in order to provide information to support forecasting, planning, control, coordination, decision making and operational activities in an organisation" [17] (the original definition had "to convert data into information products" instead of "to provide information"). Additional to their definition, the authors rightly remark that the definition does not refer to information technology, giving the example of a set of accounting ledgers for a "'manual' information system". This decoupling of the information system concept from IT systems is also a core awareness in Soft Systems Methodology, which is convincingly exemplified by their description of the information system presented in the section below.

5.2 The Information System Which Won the War

Soft Systems Methodology focuses on the understanding of humans of their business processes, and the meaning of information in the processes. It focuses on information and sense making, not on IT and “hard systems thinking” (the belief that the world contains interacting systems that can be ‘engineered’ to achieve their objectives [18]). Information in organisations is not about hard logical systems, but about soft human systems coping with a messy world where boundaries are not always clear and where organisational objectives may be conflicting.

In Checklands and Holwells analysis of the field of Information Systems the chapter “The Information System Which Won the War”, analysing the way information was organised in the Battle of Britain in 1940, is a highly illuminating example of organising information for critical processes [12]. It shows how information can be combined from multiple sources and carried by multiple technologies (radar, radio, physical maps, face-to-face coordination). Especially interesting in this respect is the filter room, which role “was to ensure the quality of the wealth of information which it fed into its own operations room”. Information from two radar chains and from human observers along the coast were interpreted, checked, and passed on to the next step, thereby integrating technical information with human observation while using human background knowledge and experience to evaluate the quality of information. The filter room was responsible for providing valid and relevant information into the room where operations were planned and monitored. The operations room would control the deployment of aircraft to meet enemy planes, up until the moment the enemy was sighted. Then command was passed to the fighter leader in the air who would communicate by radio with the pilots.

The story discussed above is not about a business organisation in stable times, but about a governmental organisation in a highly unstable time of war. Still, in the story the same basic elements can be discerned: (1) high level perception of the environment and preparing the organisation for coping with threats and opportunities in the environment; (2) operational interaction with the environment, committing to actions; (3) planning and controlling the execution of the actions in the operation room; (4) the control during the action based on perceptual information, direct supervision and a lot of background training and experience in earlier action. It is also about a mixture of technologies, partly “legacy” (radio), partly subject to continuous and rapid technological development (radar), and partly evolving organisational structures. Another relevant element of the story is the use of a special language: “‘Bandits three o’clock angels 13’ meaning ‘Enemy are due east at 13 000 ft’”. Standardisation of this language served two purposes: clarity of meaning as well as “to make it easier for the pilots to understand crackling radio messages in a noisy cockpit”. Such codification is an example of classical information theory by Shannon and Weaver, which assumes a closed world with predefined possibilities.

The relevance of this method for information system development was discussed in an earlier paper [11]. However, SSM is lacking a deeper analysis of the nature of information involved in business processes, and its impact on deciding which part in the information system is to be allotted to IT systems.

5.3 Constituting Elements of a Business Information System

Based on the notion that information shapes behaviour, that information comes in many forms, and on the definition of information system discussed above, the components of a business information system are visualised in Fig. 2. At the bottom are organisational culture, patterns of behaviour and background knowledge, together providing the general background against which information is interpreted. On the right side we find highly standardised information such as master data and transactional information. The latter contains both external and internal orders and transactions (belonging to business agreements respectively internal planning). On the left side we find information about specific commitments and expectations related to the fulfilment of business agreements. Such information can be very general, based on business policy: "never deliver less, 5% extra is always allowed". Or it is specific to more specific markets or individual customers: "always print the customer purchase reference on the pallet labels". Or it is specific to a specific (set of) order(s): "add a promotion sticker on each package in products delivered between May 1st and May 6th". Additional remarks or points of attention are also in this category, such as asking for extra checks after a customer made the same complaint for several deliveries.

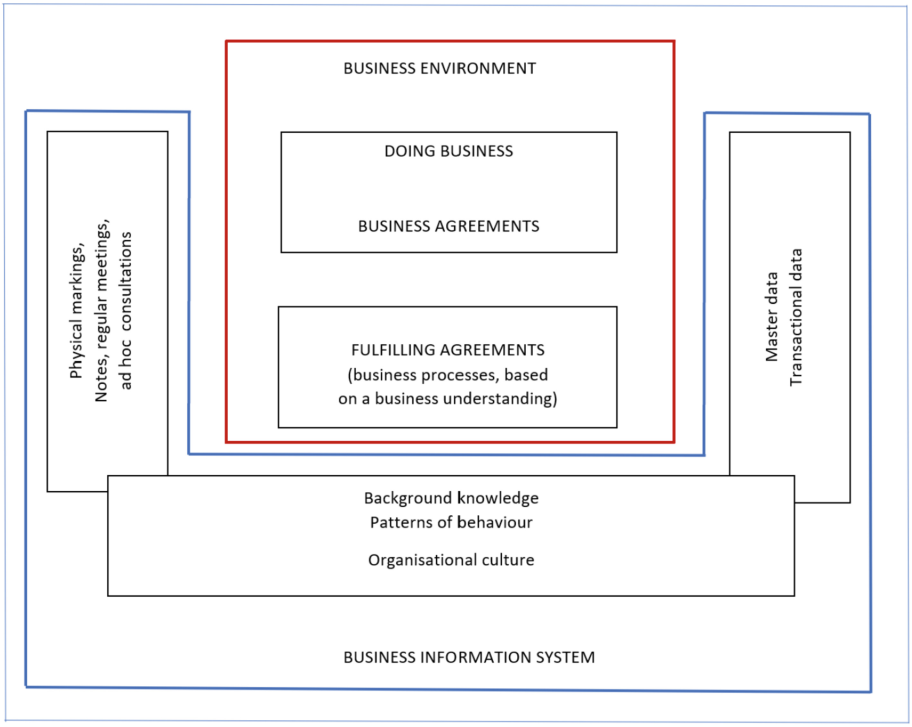

Fig. 2. The constituting elements of a business information system

Projected on the Information System Which Won the War, we find the elements of background information culture represented by both the recruiting of ex-pilots for the role of sector controllers, and also by the familiarisation of pilots with the workings of the ‘ops room’, so that they would understand the difficulties of the controller’s job. Providing reliable factual information about movements of enemy planes was a two-step process. The first step was perception by radar and by sight at coastal stations, the second step was processing those observation data by the filter room. Tactical decisions would be guided by directives from higher up in the chain-of-command. General developments and lessons learned would be discussed in regular meetings.

6 Implications for Information System Development

The analysis in the previous sections has consequences for the approach to developing business information systems. The issues discussed in this section are meant to make explicit what is probably implicitly observed in many ISD projects (especially in agile methods with emphasis on frequent feedback from the user). It requires a change of focus from IT viewpoint to business viewpoint, which (1) makes the business viewpoint leading in ISD; (2) avoids the one-sided focus on IT systems in ISD; (3) makes the need explicit for deliberately choosing the right information channels, based on an awareness of possibilities and constraints of IT systems as logical machines and (4) makes the need explicit for a practical integration of heterogeneous information in the working place.

6.1 Information Analysis

When the focus is on the informational needs of the business processes, two basic questions in analysing information in business processes are:

1. What information does someone (or some system) need to do the job in the business process?
2. What information does someone (or some system) need to produce so that other persons (or systems) can do their job in downstream processes

Of course, the focus is on information whatever its form, so these questions must not discriminate between kinds of information. After these questions have been asked, answered and validated for the business processes involved, the next step is to match sources and production of information. The general criterion (again, whatever the form of information), is that for each identified need of information a source must be identifiable (more than one source is possible, but might turn out to be problematic). An answer to the source of information might be: “when a nearly empty pallet is moved out of its pick location a bit, it is a sign to the forklift driver to restock that location” (an example of a shop floor convention). Also, for all information that is produced in business processes at least one process which uses this information should be identifiable (in case of multiple use, further checks might be important: do the multiple uses indeed require exactly the same information?).

6.2 Requirements Engineering

If the information system is about all kinds of information, requirements engineering (RE) should also be about all kinds of information flows. Hence, RE should produce requirements for IT systems as well as requirements for the business organisation. Such requirements are about organising the 'functional flows' of information. Flows can be organised for structured data (forms on paper or in IT systems), or for less-structured information (regular meetings, ad-hoc consultations). In Mintzberg terms of organisational structures: either by codification (standardisation), or by human interaction (direct supervision or mutual adjustment).

Another kind of requirements for the organisation is about organising the environment for the functional flows of information. It is about setting up coding systems for master data, writing guidelines for assigning and recognising units-of-handling and their references in the physical world, on paper and on screens. A third kind of requirements is about organising the working place, where heterogeneous information flows must be integrated. The organisation must ensure that the information provided (or to be produced) fits to the physical circumstances and fits to the capabilities of staff involved.

6.3 Design of a Business Information System

The design of a business information system is about designing "a group of interrelated components that work collectively to carry out input, processing, output, storage and control actions in order to provide information to support forecasting, planning, control, coordination, decision making and operational activities in an organisation" The focus is "to provide information" to business processes.

The "interrelated components" are heterogeneous in more than one sense, as pictured in Fig. 2. Part is background information, based on experience, training and acculturation. Part is standardised and often codified. Part is non-standardised and often non-codified. Another distinction is that some information is "clean" with objective delimitation (such as someone's social security number, or the license plate of a car). Other is "clean" but with conventional delimitation (e.g. production date, as defined by the QA department) or discretionary delimitation (e.g. operational staff – following general guidelines – decide when to start a new production lot). Some numeric information is determined, some undetermined (e.g. quantity to be shipped to customer X: "1000 pieces" vs. "everything"). Some information is factual, other directive or normative (e.g. "ASAP"). Information can use different kinds of sign systems: some is based on natural language (partly general, partly specific belonging to the organisation or discipline, partly specific by habit), other on formal language (computers), some on pictorial signs. As shown in the section about kinds of information in business processes, a complicating factor is that apparently clean numerical information often has a non-clean component indicating allowable deviation from the number.

So, in designing a business information system, information flows have to be assigned to information channels. Partial systems such as IT systems, organisational communication flows, physical marking systems have to be designed. This is a creative process, and from the design process additional questions for information analysis may follow. Also, requirements might be added, deleted or modified (requirements of any kind).

6.4 Pathologies in Information System Development for Business

Wynn and Clarkson discuss three kinds of process pathologies in design and development processes, which could be applied to information system development for business as follows: (1) conceptual pathologies, representing inadequate understanding of the process; (2) organisational culture pathologies, representing inadequate understanding for what makes the organisational work (also: for its distinctive capabilities); and (3) organisational structure pathologies, representing inadequate understanding of tasks and responsibilities in the organisation [19]. A fourth kind can be added, informational pathologies, representing inadequate understanding of the nature of information in business processes, and the interdependency of various information flows. The hard systems thinking as described by Checkland [3] would be an example of all first three kinds of pathologies, exhibiting a purely rational view on business processes while disregarding human interpretation and responsibilities. However, just as in a business organisation mismatches between the formal organisation and organisational reality can be compensated for by employees on the job (the so-called informal organisation describing how the organisation really works), project teams working on information system development will often compensate for one-sidedness of methodologies and address organisational issues as well (but sill with a possible rational bias). Of course it would be better that methodologies address all relevant issues of heterogeneous and interdependent kinds of information channels, as Soft Systems Methodology is meant to do (but missing the point of making informational pathologies explicit).

6.5 Cost and Value of Information, Pragmatic Choices in ISD

The added value of information in a business process is its contribution to the quality of the business process. To have value at the working place, the information must be timely, relevant and understandable, which is dependent on properties of the business process itself as well as properties of the actor (human or machine) in that process. The information must fit in the process, and must fit in the mental world of the human actor. Making information available to be used in business processes involves cost. Some of the cost is investment, some is maintenance, some is operational. As investment counts of course the cost of projects for information system development, including the organisation and implementation of coding systems, the initial setting up of master data, and the setting up and training of operational procedures for dealing with information flows between processes). More general training processes for providing personnel with the necessary background to do their job in a business process, including their understanding the various kinds of information related to their job, are also part of investment cost. Keeping master data up-to-date is an example of maintenance cost. Another example would be part of the mechanisms for internal control: systematically checking the quality of the information in business processes including its fit to processes and personnel, and taking corrective action when needed. Operational cost is about the time workers in business processes spend in getting and interpreting the information they need, and also cost of losses as a consequence of insufficient or misinterpreted information (failure cost).

In developing an information system, choices have to be made about the scope of the IT systems, and how information flows processed by the IT system cooperate with background information and information flows via other means. As an example: in some organisations, for order fulfilment it is enough to provide the shop floor with simple lists with delivery dates and quantities of items ordered by customers. Shop floor personnel have the knowledge and experience to take care of everything else by self-organisation and mutual adjustment. In most cases, however, such ordering lists are input for a planning process which has as output more detailed internal orders. Still, such internal orders will require some degree of knowledge and experience to be used in the right way. Striking the right balance between the various information flows, and warranting the coherence between them and with the mental world of the user will have a big impact on cost and value of the information in business processes. It must be based on concrete experience of the actual processes, and not only on an abstract functional model of it. If the system does not fit, people in processes will find their own solutions, and they might be quite inventive at it. Business processes are running smoothly, everyone is satisfied, and the system seems to be working. What is hidden below the surface, however, are the tweaks, adaptations and practices in the processes to make it work.

7 Conclusion

The argument in this paper can be recapitulated as follows:

- Standard situations are solved by standardisation of processes and information;
- 'Frayed edges' and minor disturbances of business processes are solved by routine patterns based on efficiency, which are often based on habits in combination with background knowledge about the interests of the customers;
- Bigger disturbances and deviations exceeding usual variability are solved by supervision and/or mutual adjustment, and involves balancing value for the customer (satisfying commitments and expectations) and value for the own company (costs, disappointed customers, orders cancelled, effects on future business)
- In case a customer order cannot be fulfilled completely, and different adjustments can be made (e.g. delivering less, later, substituting products), interpretation and possibly consultation is required
- In case not all customer orders can be fulfilled simultaneously, interpretation and possibly consultation is required who gets what, how much, and when. Also, what are the consequences for the customer and for the own company (see above: costs etc.)

In short: business processes require a combination of standardised information, background knowledge, and contextual information about customers and their orders. Often interests and norms must be interpreted and balanced, which requires information about the actual business context.

The consequences of the above:

- In the development of a business information system, all kinds of information flows should be taken into account, regardless their form or contents

- Partly the design is about structuring flows (either processed by IT systems, or otherwise), and partly it is about creating affordances (applicable to both IT systems and other information flows), making it possible to react to unforeseen circumstances. This applies especially to the registration function of the information system, which should afford the registration of whatever actually happened, regardless of intentions, planning and norms. This is the only solid basis for accountability in the organisation.

While the argumentation in the paper is focused on business-to-business and on manufacturing, the gist of the argument is meant to be applicable to other types as well: service industry, business-to-consumer, public organisations. The differences are gradual (goods/services; business/consumer; private/public), different types of organisations have different profiles, different norms, are subject to different laws. Web-based business-to-consumer is highly standardised and impersonal, but still subject to consumer law and still dealing with customer complaints. And it is still dependent on building a reputation of reliability. Public organisations are serving their citizens and not doing business with consumers (although the neoclassical economists tried to deny this). Future work might cover the elaboration of the theory of the firm for different types of business, and the modification of the theory of the firm to a "theory of the public organisation" for governmental organisations. Companies delivering public goods such as railways or water might require a third type of theory, they are perhaps best analysed as business-to-citizen instead of business-to-consumer. Whatever the theory: any organisation has to deal with a mix of different kinds of information in its organisational processes.

As a final illustration of the point made in this paper about dealing with a dynamic environment, it is useful to refer to the current turbulence pressures on our world-wide trade and logistic systems [20]. How do business processes and their information systems cope with such examples of radical uncertainty [21]?

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Data Contracts in Data Mesh: A Systematic Gray Literature Review

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Abstract. Data mesh is a decentralized data architecture that shifts the responsibility of managing data to data domains, allowing them to deliver domain-specific data as products tailored to meet customer needs. It promotes the idea of dynamically discovering and composing data products, forming a network of interacting data products. In this context, a key challenge is monitoring and regulating data exchanges between data products. To address this issue, data contracts have been proposed as formal agreements that define and enforce terms for exchanging data between producers and consumers. However, there is little academic literature on the topic, leaving a research gap in understanding it in detail. At the same time, since the data contract concept emerged from the industry, there is a considerable number of articles on it from practitioners, also known as *gray literature*. Hence, we conducted a systematic review of the gray literature on data contracts to clearly define the concept, identify the motivations for adopting it in organizations, develop guidelines for its implementation, and establish a research roadmap for further studies.

Keywords: Data contracts · Data mesh · Data products · Data domains

1 Introduction

The rate at which data is created, captured, copied, and consumed has been growing rapidly over the last few years, and this trend is expected to continue [10]. However, organizations can only rely on their data when the quality of the data is high, the data is stored securely, and data processing is implemented effectively [5]. To achieve these requirements, organizations use big data architectures to ensure the proper collection, processing, storage, sharing, and governance of data. Over time, data architectures such as data warehouses and data lakes have been developed to handle the increasing demand for data within organizations [6]. These data architectures typically employ a centralized operational model, where a single data platform team manages data from business

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domains. However, unclear data ownership and the central team's lack of domain expertise often make it a bottleneck for scaling value creation from data as the number of data producers and consumers increases [7,13].

To address the limitations of centralized data architectures, Dehghani [7] has proposed the *data mesh*, a domain-driven, decentralized architecture for managing enterprise data at scale. Each domain in the organization is responsible for creating products based on its domain data. A data product takes raw domain data (and optionally the data from other data products), transforms it to match the expectations of the consumers, and delivers the transformed data to the consumers, who are typically other data products or end-user applications [13,36]. A data mesh, an interconnected network of data products, is formed when the data is exchanged between data products at runtime.

A key challenge for data mesh is the safe and reliable composition of data products [13,35,36]. To address this issue, Dehghani [7] introduced *data contracts*, formal agreements between data producers and consumers that outline data ownership, terms of data offering and use, and guarantees. It forms the basis for defining and monitoring service-level agreements between data product stakeholders. While practitioners and researchers consider the data contract as a key piece of the data mesh puzzle [13,35,36], little academic research exists on the topic. At the same time, we noticed many gray literature sources related to data contracts, such as blogs, articles on practitioner websites, and white papers. The gray literature is commonly used in the research community to synthesize the knowledge on the concepts that primarily emerged from the industry or to gather practitioners' perspectives on topics [11,13,21].

In this paper, we present a systematic gray literature review (SGLR) [11] that aims to synthesize knowledge from data contract gray literature sources, improving the current understanding of data contracts. By analyzing 45 gray literature articles, we identified the key elements of a data contract, its purposes, guidelines for implementing them within an organization, and potential research challenges. We believe our findings can help practitioners design and implement data contracts, as well as guide researchers in identifying key directions for further research into data contracts.

This paper is structured as follows. Section 2 explains data mesh. Section 3 discusses our SGLR methodology. Section 4 presents the findings from the review, organized into four research questions. Section 5 outlines the potential threats to our study, and Sect. 6 reviews the related work. Finally, Sect. 7 concludes the paper.

2 Background: What Is Data Mesh?

A data mesh provides a decentralized data architecture and a socio-technical approach to managing and exchanging data within an organization, aiming to create value from data at scale [7,13]. It comprises four principles: domain ownership of data, data as a product, computational federated governance, and self-serve data platform. The first principle shifts the responsibility for managing data and offering it as products to business domains that produce raw data or aggregate data from other domains to create value-added data assets, such as enriched datasets and machine learning models. Data products are the units of value exchange in a data mesh, and they ingest, process, and serve data assets [7,13]. To ensure that data products managed by autonomous domains

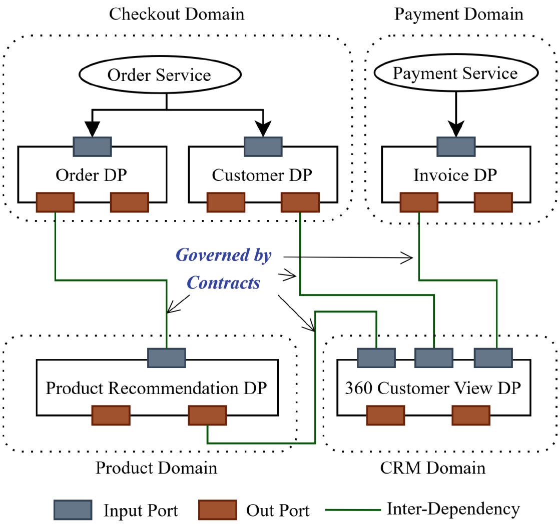

Fig. 1. A data mesh - an interconnected network of data products (DPs), governed by data contracts [13]

can interoperate and compose, the federated computational governance defines and enforces interoperability standards, as well as data exchange and usage policies. Finally, the self-serve platform empowers domain teams to easily build, share, manage, and consume data products by providing the necessary tools and services.

Figure 1 shows an example of a data mesh [13]. There are five data products spread across four domains. The data products order, customer, and invoice ingest and process the raw operational data (e.g., orders and invoices) produced by the microservices used in the business processes of the corresponding domains. In the data mesh, such data products are called source-aligned products [7]. These data products offer access to the processed source data through interfaces (output ports in the data mesh terminology [7, 13]). The 360-degree customer view and product recommendation data products ingest and aggregate data from other data products. Such products are called aggregate or consumer-aligned data products. To ensure that data products can interact reliably and safely, data contracts between data products (or their owners) define and enforce the conditions and terms of exchanging and using data.

3 Research Design

Very little academic literature is available on data contracts. As such, a systematic review of the relevant gray literature (GLR) is conducted to understand the topic better. We followed the guidelines proposed by Garousi et al. [11] for conducting gray literature reviews. We also consulted several other systematic gray literature studies [13,21,38]. Figure 2 provides an overview of our SGLR methodology, which consists of three phases, each comprising multiple steps (similar to [21]).

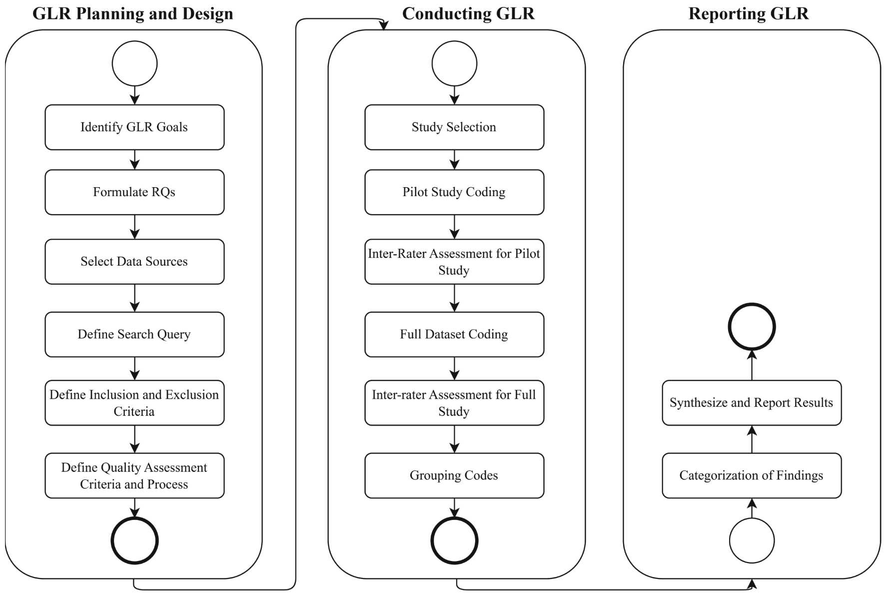

Fig. 2. Systematic gray literature review methodology [21]

3.1 Planning the Review

As in most other SGLRs [13,21], we only consider textual sources such as reports, blogs, articles, forum posts, tool documentation, presentations, transcriptions of webinars and keynotes, and white papers. The primary objective of our review is to explore the concept of the data contract. In particular, we aim to identify the elements of a data contract to create a metamodel for it, to understand the factors that influence the adoption of data contracts in organizations, to gather guidelines for implementing data contracts, and to develop a research roadmap to advance knowledge about data contracts. Given these research goals, we created a search query to find the relevant sources. We tested several variations of the query and decided to use the following query based on the quality of the search results we received. We primarily used the Google search engine to find the articles, as in other SGLRs [13,21,34].

Data Contract AND Data Mesh AND (Enforcement OR Definition OR Implementation OR Design OR Driver OR Governance OR Challenge OR Issue OR Problem)

Additionally, reference lists and backlinks mentioned in the retrieved gray literature sources were used to complement the original sources [11]. We executed the search on March 27, 2024. We checked each return result page and stopped when new related articles no longer appeared. This resulted in 104 data sources. Next, we filtered data sources based on the exclusion and inclusion criteria listed below.

Inclusion Criteria:

- Articles in English
- Accessible without an account
- Matches the focus of the study

Exclusion Criteria:

- Sources not accessible without an account
- Sources restricted by paywall
- Duplicate article from different sources
- Sources that are too short and do not contain enough data

To ensure the selection of the most appropriate sources, we also used the quality assessment checklist used by Abel et al. [13], which includes the following criteria:

- Is the publishing organization reputable?
- Has the author published other work in the field?
- Does the author have expertise in the field?
- Does the source have a clearly stated purpose?

The first two authors of this paper performed the article section and quality assessment. For a data source to be included in the study, a mutual agreement on its inclusion had to be reached. After assessing all the data sources, a final set of 45 was selected. We used the Cohen Kappa coefficient to measure the inter-rater reliability [3]. The inter-rater assessment had a coefficient of 0.62 and an agreement percentage of 79%, indicating substantial agreement between the two raters.

Table 1 provides an overview of the selected studies. It includes the type of data source, content, year of publication, and venue for each source. The complete list of articles can be found in our replication package (see Sect. 3.3).

3.2 Conducting and Reporting the Review

After gathering all relevant data sources, we conducted a qualitative analysis of them using thematic analysis methods [29]. Inductive coding was used to create an initial overview of the knowledge contained within the sources. After making the initial codes, structural coding was used to pinpoint topics more accurately. This was done by summarizing the initial topics into a single word or short phrase [29]. The coding was performed in *Atlas.ti* qualitative data analysis tool[1]. The first author of this paper coded all the literature sources, and the second author reviewed the coding results. All disagreements were resolved through discussion.

3.3 Replication Package

The complete list of sources and the qualitative analysis of these sources performed using *Atlas.ti* tool are available online[2].

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[1] https://atlasti.com/.

[2] https://doi.org/10.6084/m9.figshare.28846619.v1.

Table 1. An overview of the selected gray literature sources

Source	Type	Content	Year	Venue
S1	Blog	Definition, Elements, Drivers, Instantiation, Enforcement	-	Datamesh
S2	Blog	Definition, Elements, Drivers, Guidelines, Challenges	2023	Airbyte
S3	Blog	Definition, Benefits	-	GetSTRM
S4	Blog	Definition, Elements, Guidelines, Challenges	2023	DataGalaxy
S5	Blog	Definition, Drivers, Guidelines, Standard, Elements, Benefits	2023	Medium
S6	Blog	Definition, Elements, Standard, Tools	-	Datacontract
S7	Article	Elements, Instantiation, Enforcement, Benefits	2024	Gable
S8	Blog	Definition, Instantiation, Enforcement	2024	blog.det.life
S9	Article	Definition, Drivers, Elements, Stakeholders	2024	Zeenea
S10	Blog	Drivers	2022	Montecarlo
S11	Blog	Definition, Drivers, Benefits, Tools, Enforcement, Instantiation	2023	Xebia
S12	Blog	Elements, Standards	2023	Substack
S13	Blog	Definition, Drivers, Elements, Tools, Enforcement, Management, Guidelines	2023	Atlan
S14	Blog	Stakeholders, Guidelines	2023	Linkedin
S15	Blog	Definition, Drivers, Benefits, Guidelines	2023	Juliana-Jackson
S16	Blog	Drivers, Tools, Guidelines	2023	Medium
S17	Blog	Drivers, Guidelines, Instantiation, Elements, Enforcement	2022	MLOps
S18	Blog	Drivers, Definition	2022	Dataproducts
S19	Blog	Definition, Elements, Guidelines, Instantiation	2022	Better Programming
S20	Blog	Definition, Guidelines, Drivers, Instantiation	-	Striim
S21	Article	Drivers, Tools, Elements, Standard, Instantiation, Stakeholders, Benefits	-	OpenDataContract
S22	Article	Elements, Instantiation, Management, Guidelines	2022	Microsoft
S23	Blog	Definition, Elements, Instantiation, Enforcement	2023	Confluent
S24	Blog	Guidelines, Instantiation, Challenges, Stakeholders, Management	2023	Dataproducts
S25	Blog	Drivers, Elements, Instantiation, Management	2023	Snowplow
S26	Blog	Definition, Guidelines, Enforcement, Tools	2022	TowardsDataScience
S27	Documentation	Definition, Elements, Guidelines	-	Datamesh-Governance
S28	Blog	Definition, Elements, Benefits, Guidelines	2023	Medium
S29	Blog	Definition, Drivers, Benefits, Standard, Instantiation	2024	Thoughtspot
S30	Visual	Elements, Instantiation	-	Informatica
S31	Blog	Definition, Elements, Benefits	-	OneData
S32	Roundtable Discussion	Standard, Guidelines, Enforcement, Challenges, Management	2023	Datameshlearning
S33	Podcast	Definition, Guidelines, Instantiation	2023	DataAsAProduct
S34	Blog	Definition, Elements, Instantiation, Enforcement	2023	Medium
S35	Blog	Drivers, Benefits, Challenges	2023	Medium
S36	Blog	Definition, Elements, Drivers, Benefits	2024	KenwayConsulting
S37	Blog	Definition, Guidelines, Management, Instantiation	2023	Atlan
S38	Blog	Definition, Guidelines, Instantiation, Enforcement, Tools	2023	acryldata
S39	Post	Elements, Drivers, Enforcement	2023	Twitter
S40	Article	Guidelines, Tools, Elements, Instantiation, Enforcement	2023	Tensorflow
S41	Article	Drivers, Definition, Stakeholders, Elements, Instantiation	-	AnjanData
S42	Blog	Definition, Elements, Tools	2024	Perigeon
S43	Blog	Definition, Drivers. Guidelines	2024	SelectStar
S44	Blog	Definition, Drivers, Guidelines, Instantiation, Benefits	2024	HighTouch
S45	Blog	Drivers, Guidelines	2023	AgileLab

4 Results

We used the data extracted from the data contract gray literature sources to answer four research questions:

- **RQ1**: What is a data contract?
- **RQ2**: Why does an organization need data contracts?
- **RQ3**: How can a data contract be implemented?
- **RQ4**: What are the research challenges in data contracts?

Table 2. Content of a data contract

Sub Category			Atomic Code			
ID	Name	Frequency	ID	Name	Frequency	Sources
1.1	Element	317	1.1.1	Access	10	S4, S7, S12, S19, S27, S28, S33
			1.1.2	Data Quality	96	S1, S2, S3, S4, S5, S6, S7, S8, S9, S11, S12, S13, S14, S15, S16, S17, S19, S20, S21, S22, S23, S24, S26, S29, S32, S33, S34, S36, S37, S38, S39, S40, S41, S42, S44
			1.1.3	Policy	26	S2, S3, S4, S5, S7, S9, S10, S12, S21, S25, S27, S36, S37, S41, S42
			1.1.4	Pricing	1	S5
			1.1.5	Schema	91	S1, S2, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S23, S24, S25, S26, S27, S28, S29, S32, S33, S34, S35, S36, S37, S38, S39, S40, S42, S44
			1.1.6	Semantics	50	S1, S2, S4, S6, S8, S9, S10, S11, S12, S13, S15, S17, S18, S19, S20, S21, S24, S25, S26, S27, S29, S32, S35, S38, S39, S40, S44
			1.1.7	Use Case	43	S1, S2, S4, S5, S6, S7, S8, S9, S12, S15, S16, S22, S23, S24, S26, S27, S28, S29, S32, S33, S34, S35, S36, S37, S38, S42, S44
1.2	Specification	141	1.2.1	API Definition	39	S2, S5, S7, S9, S10, S11, S13, S14, S16, S17, S18, S19, S20, S23, S24, S26, S27, S28, S32, S35, S37, S39
			1.2.2	Ownership	47	S2, S4, S5, S7, S8, S9, S10, S12, S14, S16, S17, S20, S21, S22, S23, S24, S27, S29, S32, S34, S35, S36, S38, S39, S40, S45
			1.2.3	SLA	24	S4, S7, S9, S12, S13, S22, S23, S25, S27, S33, S36, S38, S39
			1.2.4	Version	31	S1, S2, S5, S7, S10, S11, S14, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S28, S32, S35, S37, S40, S42
1.3	Type	186	1.3.1	Data Product API	170	S1, S2, S3, S4, S5, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S25, S26, S27, S28, S32, S33, S34, S35, S36, S37, S38, S39, S40, S41, S42, S44
			1.3.2	Data Usage Agreement	16	S1, S4, S5, S7, S9, S22, S27, S32, S41

4.1 RQ1: What Is a Data Contract?

According to the gray literature, at a high level, a data contract represents the contractual agreements between a data product owner and a consumer regarding the offering and use of a data product. Table 2 shows the key themes we identified from the gray literature concerning the content of a data product. In the table, the sources are the gray literature articles, and the frequency indicates the number of times a given atomic code appears in the coding results across sources.

Elements of a Data Contract. A data contract comprises several elements (**C1.1**). First, the location of the data product and how to access it through its endpoints are defined in the data contract (**C1.1.1**). A data contract should tell data product consumers what queries they can send to the data product's endpoints. Secondly, the data contract specifies expectations and standards for data quality, making them explicit (**C1.1.2**). It specifies a set of conditions that should prevent downstream consumers from experiencing data quality problems themselves and thus increase data confidence. The quality of a dataset is characterized by using dimensions, such as accuracy (the degree to which data is correct, precise, and free from errors) and completeness (the degree to which all required data values are present) [28]. Additionally, a data contract can help achieve regulatory compliance for data management operations, for example, ensuring that sensitive data is shared in a way that complies with the GDPR (General Data Protection Regulation)[3]. The different policies (e.g., data encoding, anonymization, and retention) that should also be applied to a data product are specified in the data contract (**C1.1.3**). Pricing (**C1.1.4**) can be included in a data contract to help explain the billing process to customers of a data product. Another essential element of a data contract is the schema definition or data model for the data being delivered from a data product (**C1.1.5**). Here, the structure and format of the data are defined, ensuring that users can use the data accurately and reliably. Moreover, the semantics (**C1.1.6**) of the data can also be explained within a data contract, ensuring its consistency and allowing for a better understanding of the data by consumers. Finally, the potential use cases and terms of use for data can also be part of a data contract (**C1.1.7**).

A data contract can define what a consumer can expect from a data product (**C1.2.1**), analogous to API specifications for web services. Data contracts are specified as an interface abstraction with a set of conditions that enable the transparent and versionable exchange of data in and across organizations. A data contract should specify multiple items related to the consumption of a data product. First, a data contract should specify the ownership of data products (**C1.2.2**). This ensures that ownership is assigned to every part of the data value chain and that the right people can be contacted in case of data errors. Additionally, the terms of service for a data product should be defined. Guarantees regarding data quality and availability, which are part of a service-level agreement (SLA) between a data producer and a consumer (**C1.2.3**), are also specified in the data contract. Finally, data contracts must be versioned (**C1.2.4**), protecting consumers from rapid changes to a data product. Moreover, the changes to data contracts should be recorded in an audit trail to support transparency and accountability.

The gray literature discussed two variations of data contracts: data product APIs and data sharing and usage agreements (**C1.3**). When the data contracts are treated as APIS, they are attached to the input and output ports of data products (**C1.3.1**). They should be machine-readable and describe how to consume the data from a data product, as well as the constraints applied. The data sharing and usage agreement (**C1.3.2**) documents specific relationships between producers and consumers. They specify the purpose and terms for data usage. Such agreements are mutual agreements between data providers and data consumers. They are created when a consumer's access to a data product is approved and can be terminated by either party if specified conditions, such as insufficient business value or poor data quality, are met. This ensures product thinking and encourages data producers to ensure consumers gain value from their data. The permissions for data access are also tied to data usage agreements.

Metamodel for a Data Contract. In summary, a data contract describes the characteristics of the data delivered from a data product, the constraints applied, and the terms of use for potential consumers. To formally and precisely define a data contract, we created a meta-model using the previously discussed findings from our gray literature and models proposed for web service contracts [18, 19, 27]. Figure 3 shows our meta-model.

[3] https://gdpr-info.eu/.

The creation, monitoring, and management of a data contract may involve multiple stakeholders, each playing different roles such as data producer, data consumer, data contract auditor [19] (an independent entity responsible for enforcing contract terms), and data steward [1] (an entity responsible for ensuring high data quality and accessibility for organizational data use cases). At a minimum, the contract should involve the data producer and the consumer. In a data mesh, data products are the value of exchange [13]. A data product will consume one or more datasets offered by another data product. A data set has a data model or schema that defines the structure and meaning of the data. For example, the data model for the *order* dataset can include attributes such as *order_id*, *customer_id*, and *quantity*. There may be various constraints on the value of each model attribute. For example, a data type constraint can indicate that the *quantity* should be an *integer*, and a custom value constraint can indicate that the *quantity* should be between 1 and 100. A data contract monitoring system can use these constraints to check the validity of the dataset received by a consumer.

In addition to the constraints on data models, a data contract should be able to define various guarantees and constraints (i.e., terms) on the service-level (SL) parameters of a data product. According to the gray literature, key SL parameters include data quality dimensions, standard software quality attributes (such as response time and availability), and data privacy metrics (such as data sensitivity level and data anonymity level). An SL parameter refers to one or metrics, and there should be functions (algorithms) to measure or calculate these metrics. For example, the data contract between the order data product (DP) and the product recommendation DP can use the SLA parameter *order_timeliness* to define that *"An order must be received by the recommendation DP within 5 min after accepting the order."*. This is related to the timeliness quality dimension. To measure it, metrics such as event arrival time and time lag between events, along with the functions to calculate them, are necessary.

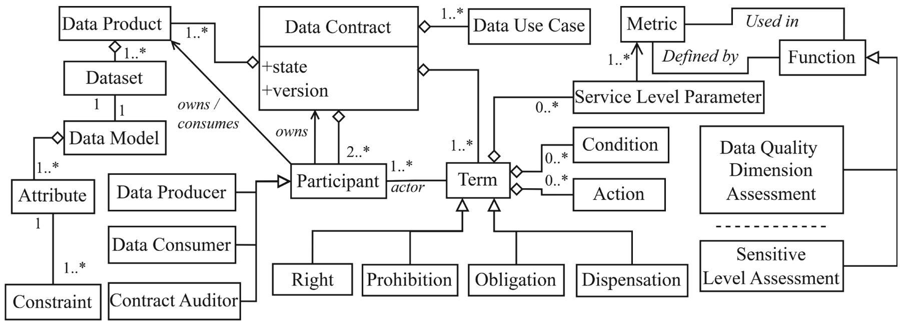

Fig. 3. A metamodel for data contracts

Table 3. Drivers for adopting data contracts

Sub Category			Atomic Code			
	Name	Frequency	ID	Name	Frequency	Sources
2.1	Drivers	323	2.1.1	Automation	133	S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S25, S26, S27, S28, S32, S33, S34, S35, S36, S37, S38, S39, S40, S41, S44
			2.1.2	Data Lineage	38	S2, S7, S9, S10, S12, S13, S15, S16, S17, S20, S22, S25, S28, S29, S32, S33, S34, S35, S36, S38, S39, S40
			2.1.3	*-by-Design	40	S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S21, S24, S25, S26, S27, S28, S29
			2.1.4	Stakeholders	39	S1, S2, S3, S5, S6, S7, S8, S9, S10, S11, S13, S14, S15, S18, S19, S21, S24, S27, S28, S32, S33, S36, S37, S38, S39, S40, S43
			2.1.5	Trust	73	S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S15, S16, S19, S20, S21, S22, S24, S25, S27, S28, S32, S33, S35, S36, S37, S38, S39, S40, S41, S42, S43, S44

A data contract should also be able to define policies that dictate what the participants can and cannot do, as well as what they should and should not do. The deontic concepts of rights, prohibitions, obligations, and dispensations are widely used to model policies [18, 19]. They can also be associated with service-level parameters. Rights are permissions that a contract participant and the associated data product have—when a given set of conditions is met, a participant can perform a particular action on a data product. For example, the order recommendation DP can read (*action*) the data from the order DP if a valid access token is provided (*condition*). Prohibitions indicate that a participant and the associated DP are not allowed to perform a specific action. For example, the order recommendation DP cannot update the data in the order DP. Obligations are actions that a participant and the associated data product must perform when certain conditions are met. For example, the data contract auditor is required to send a warning message to the order DP owner if the value for the SL parameter *order_timeliness* is greater than 5 min. Dispensations indicate that a participant or the associated data product is no longer required to perform a specific action. For example, the order DP no longer needs to keep a record of an order after delivering the relevant order information to the product recommendation DP.

4.2 RQ2: Why Does an Organization Need Data Contracts?

From the reviewed literature, we identified five key reasons that can drive the adoption of data contracts within organizations (Table 3).

Automated Declarative Data Validation (2.1.1). When the data are exchanged between different data products, the changes to the structure and quality of the data sent by the upstream data products can negatively affect the downstream data products. For example, changing the data type (from integer to string and vice versa) of a column in data produced by upstream data products can break the data transformation logic in downstream data products, leading to inaccuracies. Data contracts can help mitigate these issues by enabling data producers and consumers to automatically enforce the agreed data formats (schemas) and other data quality constraints, such as ensuring that the value for the price column is a floating-point number and cannot be negative. When written in a templated interactive machine-readable language such as YAML or JSON, a data contract can serve as a basis for schema validation, data quality testing, and monitoring. For example, test cases can be developed to check the potential violations of a schema or a quality constraint defined in the contract. These test cases can be executed automatically before serving data to consumers and/or ingesting data, allowing for the detection of contract violations and sending warnings to the responsible parties.

Improved Data Lineage (2.1.2). In a data mesh, a particular dataset originates from a data source and moves through the interconnected networks of data products to reach its ultimate point of usage. Along this pathway/journey, various data operations can be applied to the dataset (e.g., removing a column, storing it in a database, and merging it with another dataset). Data lineage records these pathways and operations using metadata, making black-box data flows transparent to data users. Data contracts define how data flows between different data products and facilitate incorporating transparency into the integration of data products or data exchanges between data teams.

Data Security and Compliance by Design (2.1.3). A data product should be able to regulate access to its data by the downstream data products and set the conditions under which the data is processed, used, and shared with other downstream data products (i.e., data access and usage control [25]). A data contract can include policies for data access and usage control. It can also explicitly mark the sensitive data, define the operations (e.g., masking and anonymization) applied to it, and usage constraints, ensuring that data exchange, storage, and processing comply with regulatory requirements (e.g., GDPR). The data lineage enabled by the contact also allows an organization to establish clear audit trails for its data. Transparency around the origin and movement of data can help assess the regulatory compliance of data management within the organization.

Enable Stakeholder Collaboration in Data Governance (2.1.4). Organizations typically use some form of data governance to ensure that their organizational data is of high quality, secure, and available for data use cases [20]. As data contracts can explicitly capture data flows or exchanges within an organization, they can simplify the enforcement of data governance policies, such as data security policies, quality control policies, and data storage policies, in a consistent manner throughout the organization. Moreover, forming data contracts typically involves collaboration and negotiation among different organizational stakeholders, as all parties must agree on the conditions under which data are stored, shared, used, and processed. For example, the gray literature suggests that data producers should take ownership of data contracts and gather input from all relevant stakeholders, such as data consumers and data stewards.

Enhancing Thrust in Data (2.1.5). Finally, data contracts help establish trust and confidence in the data. When there is an infrastructure in place to monitor and enforce data contracts, data consumers can rely on the guarantees established in these contracts. This enables downstream data products to trust the data they ingest and use from upstream data products [7,13]. Data contracts can protect downstream users from unexpected data changes and data quality issues. For example, the data lineage supported by data contracts enables data auditing and troubleshooting, helping organizations to identify the origins of data quality issues. The data consumers can also use the lineage information to assess the trustworthiness of the data.

Table 4. Data contract implementation

Sub Category			Atomic Code			
	Name	Frequency	ID	Name	Frequency	Sources
3.1	Instantiation	158	3.1.1	Standardization	39	S1, S2, S8, S10, S17, S22, S28, S33, S44
			3.1.2	Everything as Code	52	S1, S2, S3, S5, S6, S7, S8, S10, S12, S13, S15, S16, S17, S19, S20, S22, S23, S25, S26, S32, S33, S34, S37, S38, S41, S44
			3.1.3	Location	4	S1, S6

4.3 RQ3: How Can a Data Contract Be Implemented?

The gray literature provides several guidelines for implementing data contracts (Table 4).

- **Organization-wide Standardization (C3.1.1).** All data product teams in an organization should ensure the data contracts they create are consistent and interoperable. The gray literature mentioned the adoption of a standard template for data contracts. While creating an organization-wide contract template and guidelines for its use can require a considerable amount of effort, it ultimately leads to time and effort savings within teams, as the standardization results in better-quality data products and fewer breaking changes in the data pipelines.
- **Everything as Code (EaC) Approach (C3.1.2).** EAC is a software development paradigm that involves managing and automating all aspects of the development lifecycle using source code and principles such as version control, testing, and CI/CD (continuous integration and continuous delivery/deployment) [31]. The source code can be in a general-purpose programming language (e.g., Python and Java) or a custom domain-specific language (DSL). Data contracts should be instantiated as versioned, machine- and human-readable code. The automated tests should be included in the CI/CD pipeline for deploying data products and data contracts to ensure that any changes to a data product or contract are tested. For example, an update to the data model of a data product can break the contract and be detected automatically if there is a test case that assesses the data product's compliance with the corresponding data contract.
- **Enforcement at both Data Producers and Consumers (C3.1.3).** Data contracts can be created before the target data is produced. They can be implemented in both input and output ports of data products. For example, before serving the data to downstream customers, a data product can check the data for compliance at the output ports. A data product consumer can execute contract compliance checks when ingesting data through input ports.

Implementing data contract monitoring and enforcement in a data product can depend on the data architecture used. Figure 4 shows how data contracts can be implemented in a data lakehouse architecture. In this architecture, there are three main data layers, reflecting the quality of the data stored: bronze for raw data, silver for clean and validated data, and gold for business-enriched data [14]. Once the data is ingested into the bronze layer storage, the data contract can be evaluated by running data quality tests and comparing the results with the expectations mentioned in the contract [33]. If a contract term is violated, the data are moved to the quarantine storage, and the data producer is alerted. Later, if the data issues can be fixed, the data from the quarantine storage can be curated and moved to the silver layer storage (see Fig. 4).

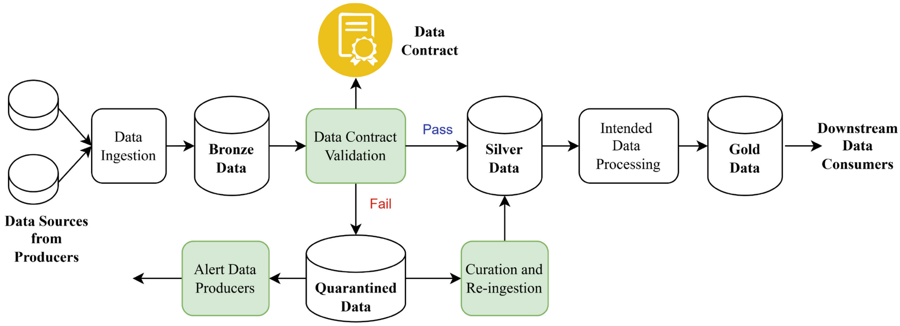

Fig. 4. Data contract implementation in the data lakehouse architecture

To provide a technology-agnostic blueprint for implementing data contract monitoring, we proposed a system architecture based on the WSLA (Web Service Level Agreement) framework, an open standard and framework for specifying and monitoring SLAs for Web Services [19]. Figure 5 shows the proposed architecture. Data product B (the consumer) ingests data from data product A (the data producer/provider) by invoking operations offered in the output interface of data product A. Each product is instrumented to produce metrics, logs, and traces necessary for monitoring the health of the data product and identifying potential violations of the terms in the data

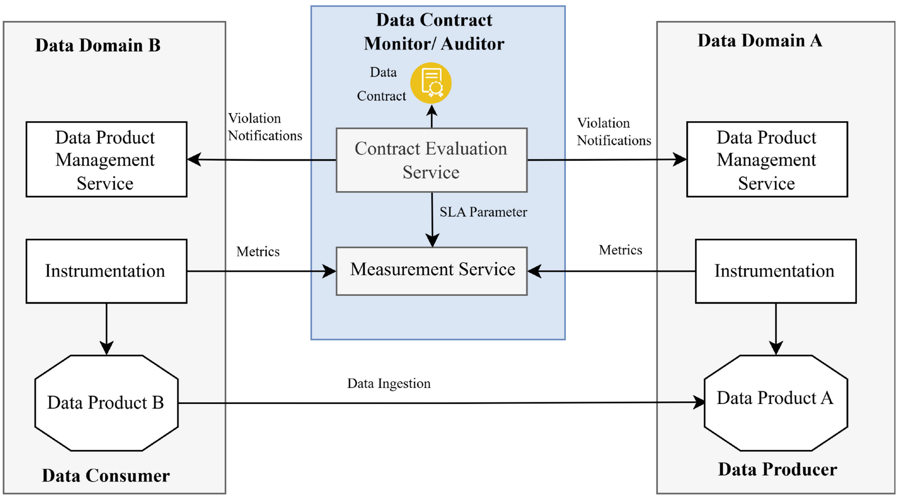

Fig. 5. An architecture for monitoring and auditing of data contracts

contracts to which the product is bound. The data contract auditor is responsible for enforcing data contracts. It uses the measurement service to collect the monitoring facts from data products and compute metrics for service-level parameters (SLAs) defined in the contracts. The contract evaluation service assesses the violation of SLAs and other constraints and agreements related to the exchanged data. If there is a contract violation, the data contract auditor notifies all involved parties. The management service in the data domain reacts to such notifications by implementing corrective actions. Some corrections can be implemented automatically, for example, changing permissions to access data, updating data retention periods, or data sensitive levels. If a data product developer needs to implement a correction to the data product manually (e.g., fixing data transformation code), the contract auditor can notify the product owner.

4.4 RQ4: What Are the Research Challenges in Data Contracts?

In this section, we discuss potential research challenges for the data contracts. We identified them by relating the practical issues mentioned in the gray literature to the research issues mentioned in the academic literature on related areas, such as Web service contracts [19] and data management [1].

Standardization. The interoperability and portability of data contracts can make them loosely coupled from their technical implementation, facilitating their negotiation, exchange, and composition, especially in the context of inter-organizational data sharing, such as data marketplaces. While there is an attempt to create an open standard[4], its maturity, scientific rigor, and adoption in organizations are not evident. There exist potentially related standards in domains such as Web services and e-business, for example, WSLA [19] and ebXML (Electronic Business using Extensible Markup Language) [12], as well as various standards for data sharing in different contexts [15]. The literature on these standards can shed light on systematically creating a comprehensive open standard for data contracts. Another open issue related to standardization is the lack of studies on formalizing and building comprehensive conceptual models, such as metamodels and ontologies, for data-contract-based data ecosystems.

From Natural Language Data Contracts to Technology-Specific Contract Specifications. Business users involved in negotiating and formulating data contracts may not be skilled in technical data contract languages and may prefer to write the contracts in natural language. Natural language processing (NLP) methods, including large language models (LLMs) [30], have been applied to translate natural language documents into software programs. For example, policy requirements can be converted into access control policies [17], and legal agreements (in text form) can be converted into smart contract code [26]. In this context, a research challenge would be to develop tools and methodologies that utilize NLP to generate data contract codes from natural language data sharing agreements.

Automated Contract Enforcement. A middleware infrastructure is necessary to monitor service-level objectives (SLOs) in data contracts and to enforce contract terms when SLOs are violated. Hence, it is essential to study the requirements, components, designs,

[4] https://datacontract.com/.

and implementation approaches for such infrastructures. To simplify the instantiation of the enforcement middleware, the tools can be developed to generate the required source codes (e.g., data quality monitoring and alerting code and executable contract rules) from the high-level specification of data contracts. A key challenge would be to maintain the consistency between the high-level contracts and the low-level code when each artifact changes. The tools are necessary to support the systematic and safe propagation of changes from contracts to the enforcement infrastructure and vice versa. Regarding enforcement middleware technologies, smart contracts in the distributed ledger can be a potential solution [16,24], especially when inter-organizational data sharing is required, which often necessitates a trusted third party.

Contract Lifecycle Management (CLM). A data contract in an organization typically goes through several phases, from negotiation, agreement, initiation, execution, performance, to termination, renewal, or expiration. A key research direction would be to study each CLM phase and develop tools and methods to support the systematic and effective execution of activities in each phase.

Exploring Practitioner Perspective. While there are many gray literature sources on data contracts, there is a lack of research on the use of data contracts in organizations. Qualitative studies (e.g., semi-structured interviews or surveys) and action research [4] can shed light on issues such as the challenges practitioners face when implementing data contracts and the best practices and solutions they adopt.

5 Threats to Validity

This section discusses the potential threats to the study's validity, focusing on internal and external threats [37].

The internal validity refers to the accuracy and reliability of the research methods used in our study. A potential threat is the risk of having missed relevant gray literature sources. To mitigate this threat, as discussed in Sect. 3, we first tried to ensure the search query is sufficiently complete. Next, to prevent the selection bias, the first two authors of this paper independently checked the relevance and quality of the articles. An inter-rater reliability assessment was conducted using the kappa coefficient, showing substantial agreement between the two raters. The qualitative analysis of the selected literature using open coding can also introduce bias. To mitigate this threat, the second author reviewed the codes and themes created by the first author, and all discrepancies were resolved through discussion.

The external validity can threaten the generalizability of our results. A potential risk to the generalizability is the use of a single source of information (i.e., gray literature). For example, an interview-based study or practitioner survey can help validate the findings from the literature study. We plan to conduct a follow-up study with data mesh practitioners in the future.

6 Related Work

Due to the topic's novelty, there is a notable lack of literature focusing on data contracts within the context of a data mesh. Among related studies, Dolhopolov et al. [8,9]

considered the properties required for data governance within a data mesh, such as data versioning, semantic augmentation of data, and contract management. Truong et al. [32] studied data contracts in data marketplaces and identified key elements for modeling a data contract, such as data rights, data quality, and pricing models. Wider et al. [35,36] discussed the roles of data contracts in enabling the reliable composition of data products as well as the exchange of sensitive data without violating privacy regulations. Heideman et al. [16] proposed a blockchain and smart contract-based approach for ensuring the consensus among data producers and consumers regarding data quality assurance in data marketplaces.

Several studies used the gray articles on data mesh for various purposes. Machado et al. [2,22,23] used the gray literature on data mesh to create a metamodel and a reference architecture for data mesh. In [34], the gray literature on self-serve data platforms in data mesh was used to build architectural design models that guide the design and development of self-serve data platforms in organizations. Abel et al. [13] systematically reviewed the gray literature on data mesh to identify practitioners' perspectives on data mesh principles and drivers for adopting data mesh in organizations. They also built three reference architectures to describe various aspects of a data mesh, including design and runtime structures.

In summary, limited academic studies exist on data contracts. The knowledge about their structure, goals, and implementation guidelines is also lacking. Several studies have reviewed and used the gray literature on data mesh to build reference architectures, metamodels, and decision models for data mesh. However, there is no systematic literature review of the gray literature on data contracts.

7 Conclusion and Future Work

A data contract between a data provider and its consumers defines their obligations and guarantees regarding the exchange of data. When embedded in the data mesh architecture, where an interacting network of data products from various data domains exchange data, data contracts enable the effective and safe generation of value from organizational data at scale. In this paper, we report the findings from a systematic review of the industrial gray literature on data contracts. We selected the gray literature because there is little academic research. We extracted data from 45 gray literature articles to define the concept of a data contract, identify the drivers for its organizational adoption, provide guidelines for its implementation, and outline potential research challenges. The results also include a metamodel for data contracts and a blueprint for implementing contract monitoring and enforcement. We believe the identified open research challenges can provide a roadmap for future data contract research.

We are developing a model-driven engineering (MDE) approach to designing and developing data contracts and products. We plan to integrate LLMs (large language models) into our MDE framework to generate the contract implementation code from the natural language descriptions of contracts.

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An Expressive Class of Well-Formed Activity Diagrams

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Abstract. *Context:* Activity Diagrams, one of the diagram types in UML, visualize sequences of instructions, including control flow. They are important (and popular) for modelling the dynamics of a (workflow) system.

Problems: It is unclear when Activity Diagrams are or are not well-defined, what the boundaries of the notion are, or which *combinations* of constructs are allowed or not allowed. It is easy to construct Activity Diagrams which are inconsistent, without any possible meaning, or with activities that are not on a path from entry point to exit point (*reachability*). For informal sketches in a discussion, this might be okay. But as a vehicle for precise system specifications, this is not sufficient. Moreover, it is hard to prove general properties for the whole class of Diagrams.

Research question: How can we specify an expressive, well-defined, consistent (sub)class of understandable constructs for Activity Diagrams in a clear way?

Main idea: We use production rules (a 'grammar') to construct composite Activity Diagrams starting from simple Activity Diagrams (i.e., basic tasks).

Solution: With only a few production rules, we constructively specify an expressive, well-defined, well-understandable and consistent class of Activity Diagrams with a clear 'control flow semantics' and other convenient structural properties.

Additional contribution: We work out and illustrate the new idea and general principles to develop a 'grammar for pictures', and apply it to Activity Diagrams in this paper. This idea and general principles are applicable for other kinds of diagrams as well, e.g., for Business Process Modeling diagrams.

Keywords: Activity Diagram · production rules · grammar · grammatical construct · well-formed diagram · consistent · control flow · reachability

1 Introduction

Activity Diagrams visualize sequences of actions to be performed, including control flow [1]. They are important for modelling the dynamic aspects of a system [2], intended to model both computational and organisational processes [3]. The standard for Activity Diagrams is found in UML. The specification of UML [2] consists of almost 800 pages.

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The objective of UML is "*to provide system architects, software engineers, and software developers with tools for analysis, design, and implementation of software-based systems as well as for modelling business and similar processes*" ([2], p. 1). Besides backward references, the UML-specification also has many *forward* references [2]. This (and other issues) makes the UML-specification hard to follow. We will dig into a few problematic issues with Activity Diagrams.

Issue 1: Meaning not Always Clear or Possible. The meaning of Activity Diagrams is usually only given informally, in natural language or using concrete examples only (e.g. [1, 4]), via ontologies (e.g. [5–8]), or via some kind of operational semantics. Their meaning is not always clear: As [1] and [3] already noted, the meaning of Activity Diagrams is not even fully defined in UML. It is easy to construct Activity Diagrams without any possible meaning. For instance, what does Fig. 1 mean (in terms of the meanings of A, B, C, D, and the condition)? Its subpart shown in Fig. 2 is called a *multi-merge*. The meaning of the multi-merge is informally described in [9] as follows: "*A point in a workflow process where two or more branches reconverge without synchronization. If more than one branch gets activated, possibly concurrently, the activity following the merge is started for every activation of every incoming branch*".

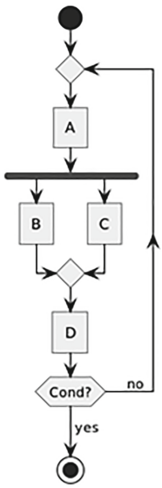


Fig. 1. What does this mean?

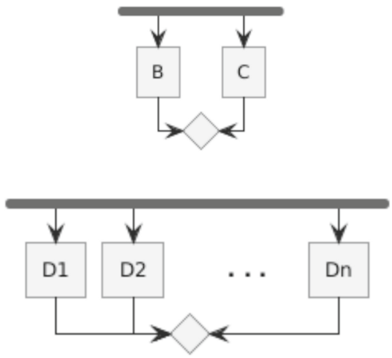


Fig. 2. Multi-merge (binary and general)

Issue 2: No Demarcation. It often stays unclear what the boundaries of the constructs are, i.e., when Activity Diagrams are well-defined, or which *combinations* of constructs are possible or should be impossible. This may lead to Activity Diagrams without a clear interpretation possibility or - even worse - two or more interpretation possibilities (*ambiguity*). For informal sketches in a discussion, the existence of diagrams without a clear semantics or boundaries might still be okay. But as a basis for precise specifications, that is not sufficient. The question remains: Which Activity Diagrams could be called 'well-defined'?

Our Approach: A Grammar for Well-Formed Activity Diagrams. We specify a well-defined subclass of constructs for Activity Diagrams by means of a clear *grammar* (or *construction rules* or *production rules*) for diagrams. A grammar is a very compact way to specify all allowed possibilities, as known from linguistics and, for instance, also used for specifying programming languages. The chosen subclass includes the most important and most frequently used constructs [9, 10]. Our grammar approach clearly differs from, e.g., a *workflow patterns* approach [9] or *graph rewriting* [11]. We could not find papers that work out our idea of an exact ‘grammar to generate pictures’. Our constructs were inspired by the constructs in programming languages and validated in various applications. They include (and simulate) the usual constructs found in programming languages. In another paper, a declarative semantics for these well-formed Activity Diagram constructs will be given [12]. That declarative semantics treats both the *statics* and the *dynamics*, in an integrated way.

These issues (and our solution) are not UML-specific but broader applicable. BPMN (Business Process Model and Notation), an alternative way of representing workflows graphically, has in fact the same issues. By exploiting the similarities between UML Activity diagrams and BPMN, we currently work out something similar for BPMN.

De rest of the paper is organized as follows. Section 2 is the main section of the paper. By means of production rules, Sect. 2 defines a class of constructs for *well-formed* Activity Diagrams. Those general diagram constructs are illustrated by a comprehensive example in Sect. 3. Section 4 explains the (quite comprehensible) flow of control in our diagrams. Section 5 mentions some other convenient structural properties of our well-formed diagrams (e.g., *reachability*). Section 6 explains that with our small set of basic constructs, many other constructs can be caught as well. The paper ends with conclusions and further work (Sect. 7).

2 A Class of Well-Formed Activity Diagrams

In this section, we define a simple class of constructs for *well-formed* Activity Diagrams by means of production rules (a ‘grammar’) for diagrams. Our production rules presuppose *Basic Instructions* and *Basic Conditions* which must be introduced per application.

Our grammar starts with 4 elementary constructs, known as *Sequential composition*, *Alternative*, *Conditional*, and *Option* (see §2.1).

The *XOR-split and -join* (choice) and the *AND-split and -join* (arbitrary order) are two other important constructs (see §2.2). For the well-formedness of the Activity Diagrams, it is important that the split and corresponding join appear together, in pairs!

There are two *loop-constructs*, representing a **while**-loop (0 or more times) and a **repeat**-loop (1 or more times), in §2.3. Theoretically, only one of these two loop-constructs would be enough because the loop-constructs can be converted into each other.

Then there are the important powerful constructs of *declarations* and *calls* (a.k.a. ‘Includes’) of sub-processes; see §2.4 and the example in Sect. 3. They help to decompose large diagrams into smaller, more comprehensible ones. Moreover, they might show the inherent structure of a large process more clearly. It also facilitates the reuse of such sub-processes, because they can simply be referred to more than once or by other processes (and could even form a library). Furthermore, during design, sub-processes can be introduced by their name only, while deferring their detailed specification to a later moment (*stepwise refinement*); an important property! Additionally, their contents can also be changed easily at such a local and isolated level.

Finally, an Activity Diagram preceded by an explicit start and followed by an explicit stop is called a *Finished Diagram* (see §2.5).

Altogether, this forms an expressive class of diagrams, as illustrated in Sects. 3 and 6, for instance. It includes the most important and most frequently used constructs in practice [9, 10].

While this paper gives the syntax, [12] gives a formal, declarative semantics for the constructs of these well-formed Activity Diagrams.

Legend. In an Activity Diagram, a basic instruction B is represented in a rectangle with rounded corners, as shown in Fig. 3, a condition C is represented in a hexagon and followed by a question mark, as shown in Fig. 4, and an arbitrary Activity Diagram D is represented as a rectangle, as shown in Fig. 5.

Fig. 3. Basic Diagram for B

Fig. 4. Condition C

Fig. 5. Activity Diagram D

Figure 6 shows two concrete examples of basic instructions and their basic diagrams, one without and one with parameters, respectively. All figures are constructed by means of the drawing generation tool PlantUML (https://plantUML.com).

Fig. 6. Concrete examples of a high-level basic instruction and a detailed instruction

The next subsections contain the production rules to construct composite Activity Diagrams from given Activity Diagrams. All Activity Diagrams 'run' from top to bottom.

2.1 Elementary Constructs

First of all, each Basic Diagram constitutes an Activity Diagram.

Furthermore, if C is a condition and D1 and D2 are well-formed Activity Diagrams, then so are the ones in Figs. 7, 8, 9 and 10. Informally, the diagram in Fig. 7 means 'first do D1, then do D2'. The diagram in Fig. 8 means 'if condition C holds then do D1, else do D2'. The diagram in Fig. 9 means 'if condition C holds then do D1 else skip D1'. The diagram in Fig. 10 means 'do D1 or skip D1'; it gives the actor the freedom to decide on it. The upper 'diamond' in Fig. 10 (and in Fig. 11) indicates a point of 'free' choice, i.e., a decision point without an explicit, prescriptive condition.

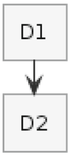


Fig. 7. Sequential composition

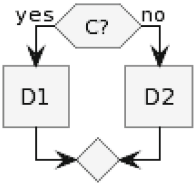


Fig. 8. Alternative

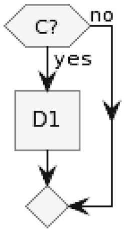


Fig. 9. Conditional

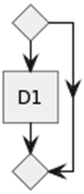


Fig. 10. Option ('maybe D1')

2.2 *XOR-Split and -Join* and *AND-Split and -Join*

If D1, D2, …, Dn (with n $\geq$ 2) are well-formed Activity Diagrams, then so are the ones in Fig. 11 (*XOR-split and -join*) and Fig. 12 (*AND-split and -join*). Informally, the diagram in Fig. 11 means 'do exactly one of D1, D2, …, Dn' and the diagram in Fig. 12 means 'do D1, D2, …, and Dn, in arbitrary order'. We emphasize that we deliberately introduce the split and the corresponding join together.

Figure 12 leaves open the possibility of (partially) simultaneous execution (*parallel behaviour*), e.g., for those that don't interrupt each other. For instance, if there is a heap of n different student registration requests waiting to be handled, and such a registration entails the generation and addition of the next free student number, and the assignment of the numbers to the students is arbitrary, then there are n! possible outcomes (be it one actor to handle that sequentially or n actors to handle that 'in parallel').

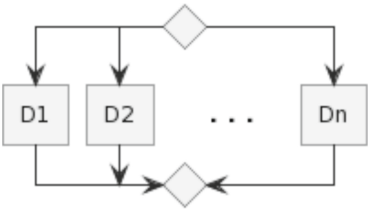


Fig. 11. Choice (XOR-split and -join)'do exactly one of D1, D2, …, Dn'

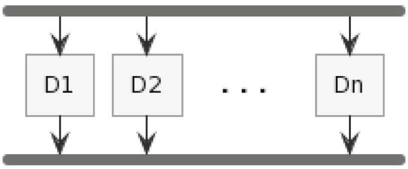


Fig. 12. Arbitrary order (AND-split and -join) 'do each one of D1, D2, …, Dn, in any order'

2.3 Loops

If C is a condition and D1 is a well-formed Activity Diagram, then so are the ones in Figs. 13 and 14. Informally, the diagrams in Fig. 13 mean ‘while condition C holds, do D1’ and the diagram in Fig. 14 means ‘do D1 until condition C holds’. With the **while**-loop, D1 is executed 0 or more times, with the **repeat**-loop, D1 is executed 1 or more times. The left diagram in Fig. 13 handles the general case; the diagram on the right is simpler but might be confusing if D1 contains two or more steps. (We only used it in Fig. 18b.)

The loops in Fig. 13 and 14 are also known as *structured cycles*, i.e., they have only one entry point and one exit point, as opposed to *arbitrary* cycles, which may have several entry points and several exit points. Arbitrary cycles are more like GOTO statements [9]. Arbitrary cycles cannot be created with our grammar. Arbitrary cycles can usually be converted to equivalent structured cycles [13].

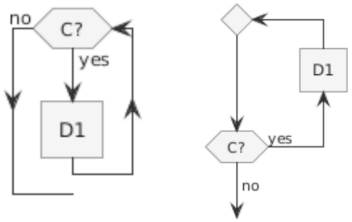


Fig. 13. **While**-loop (0 or more times) left: general; right: 1 step only

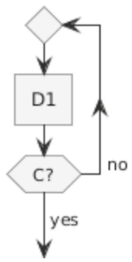


Fig. 14. **Repeat**-loop (1 or more times)

2.4 *Declaration* and *Call*

Figure 15 introduces the ‘process name’ P as standing for Activity Diagram D1. Figure 16 is an Activity Diagram representing a Call (a.k.a. an ‘Include’): Informally, the diagram in Fig. 16 means ‘perform the action(s) where P stands for’. P can be parameterized, e.g. *RegisterStudent(name n, address a, birth date d).* The same process name should of course not be declared twice.

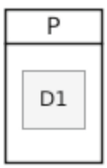


Fig. 15. Declaration

Fig. 16. Call (a.k.a. ‘Include’)

2.5 Finishing Touch

To finish an Activity Diagram, the final result is usually preceded by a *start* circle and followed by a *stop* circle, as shown in Fig. 17. We call it a *Finished Diagram.*

Hence, a Finished Diagram has one begin point and one end point. Typically, a diagram with several terminating nodes can be transformed to an equivalent diagram with only one terminating node according to [9].

We only use a start and stop circle for the final result, not for the intermediate sub-processes: Sub-processes should not stop intermediately but pass back the control to the calling process. (See Fig. 18 for examples.) In this way, the 'sub-diagrams' can be moved in and out of other diagrams without further ado.

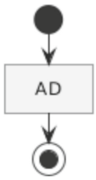
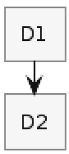
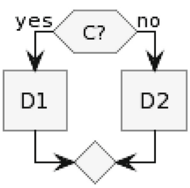
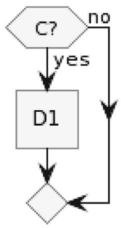
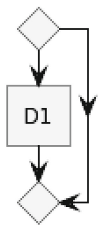
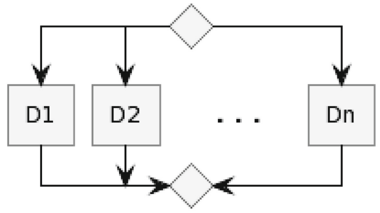
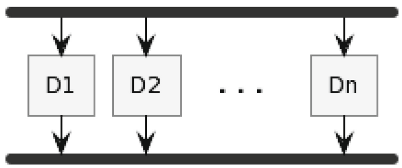


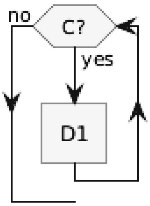
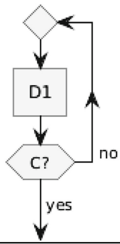
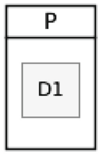
Fig. 17. Finished Diagram

2.6 Summary

The next tables list the foregoing production rules. Each column in each table subsequently contains (1) the common name of the composition rule, (2) the composite Activity Diagram, and (3) its meaning, expressed informally.

Sequential composition	Alternative	Conditional	Option
			
First do D1, then do D2	If condition C holds, then do D1 else do D2	If condition C holds, then do D1 else skip D1	Do D1 or skip D1

Choice (XOR-split and -join)	Arbitrary order (AND-split and -join)
	
Do exactly one of D1, D2, …, Dn	Do each one of D1, D2, …, and Dn, in arbitrary order

while-loop	**repeat**-loop	Call (‘Include’)	Declaration
			
While condition C holds, do D1	Do D1 until condition C holds	Perform the action(s) where P stands for	The (process) name P stands for D1

Below, we schematically present our ‘grammar for diagrams’ in a classical grammar-like way (where the nonterminal <BD> stands for Basic Diagram, <AD> for Activity Diagram, <FD> for Finished Diagram, and <PN> for Process Name):

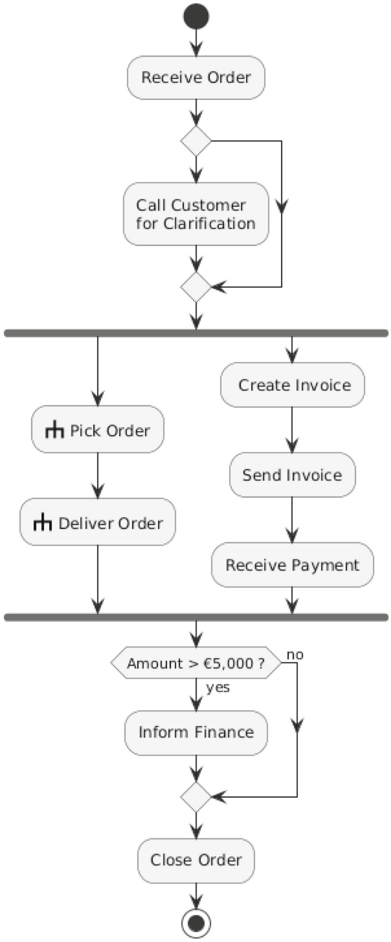
<AD>::= <BD> | <AD>→<AD> | … | <PN>
<FD> ::= ●→<AD>→◉

3 A Comprehensive Example

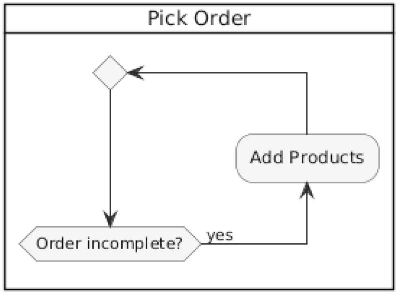
We give an example in which almost all our constructs appear (Fig. 18), based on a much simpler example in [14].

The main process starts with *Receive Order* and ends with *Close Order* (Fig. 18a): After receiving an order, the customer might be called for clarification, but not necessarily. Then two processes take place ‘in parallel’: (a) Preparing and delivering the order and (b) Handling the payment. When all that is finished, the Finance department is explicitly informed if (and only if) the amount was more than €5,000. Then the order is closed.

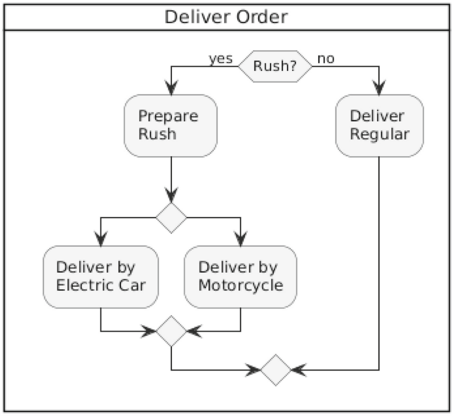
The sub-processes *Pick Order* and *Deliver Order* are worked out in further detail in Fig. 18b and 18c: *Pick Order* expresses to add products as long as the order is incomplete. *Deliver Order* contains an explicit decision between regular and rush-deliveries. A rush-delivery is either by electric car or by motorcycle.



a. Main process



b. Sub-process *Pick Order*



c. Sub-process *Deliver Order*

Fig. 18. **a.** Main process **b.** Sub-process *Pick Order* **c.** Sub-process *Deliver Order*

4 Flow of Control

As a general invariant, in each diagram the flow of control (the order in which individual instructions are executed or evaluated) will 'run' from top to bottom. Alternatively formulated, the flow of control follows the arrows. In more detail:

In the diagram in Fig. 17, the flow of control starts at the top (●) and ends at the bottom (◉), *if it ends*: See the remarks regarding Figs. 13 and 14 below. The flow of control in each diagram in Figs. 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16 starts at the top and goes towards the bottom. In the diagram in Fig. 11, the control flow 'goes through' just one of the diagrams D1, …, Dn. In the diagram in Fig. 12, the control flow 'goes through' all the diagrams D1, …, Dn, after which there is one single flow of control left.

In the diagrams in Figs. 13 and 14, the control flow starts at the top, goes zero or more times through the loop, and ends at the bottom, *if it ends*: It might be that the loop never ends, namely if the condition stays true in Fig. 13 or stays false in Fig. 14.

So, at the end of each Activity Diagram, there is at most one ‘running control flow’. Given this simple flow of control, we don’t need a complex ‘token-calculus’ with, e.g., Petri-nets.

5 Some Other Structural Properties

All our well-formed Activity Diagrams and Finished Diagrams have some other convenient structural properties as well. For instance:

(1) All well-formed Activity Diagrams and Finished Diagrams have 1 entry point and 1 exit point. The entry point of a Finished Diagram is often called an *initial* state and the exit point of a Finished Diagram is called a *final* state.
(2) In each well-formed Activity Diagram and each Finished Diagram, all activities are on a path from its entry point to its exit point. So, no ‘loose ends’. Consequently, all its activities are reachable from its entry point via a path, and the exit point is reachable from each of its activities via a path (*reachability*).
(3) Because a split and the corresponding join always appear together (§2.2), in pairs, a multi-merge (Fig. 2) cannot be created with our grammar.

We can prove those properties usually by induction, because the properties are invariants of all the constructs given by the grammar.

6 What About Other Possibilities?

Several seemingly ‘other’ constructs can also be caught with our basic constructs. For instance, the so-called *OR-split and -join* can be considered as an *AND-split and -join* with conditionals as ingredients. See Fig. 19.

Combinations are also possible, of course. For instance, Fig. 20 expresses that, in arbitrary order, D1 *must* be done, D2 *may* be done (or skipped), and D3 *must* be done if condition C holds and D3 *must not* be done if condition C does not hold.

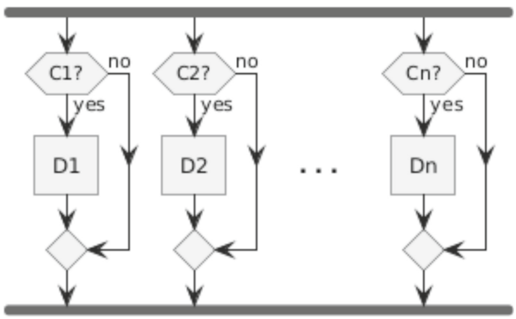


Fig. 19. The OR-split and -join

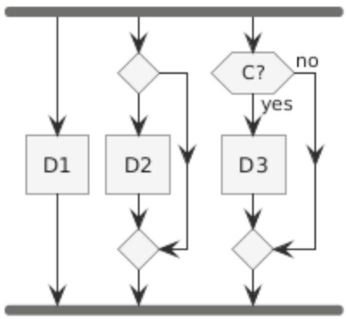


Fig. 20. A combination

The AND-split and -join expresses that two (or more) activities, say D1 and D2, can be done in any order: D1; D2 or D2; D1. (For each individual case, an employee might decide on it.) But often an organisation allows only one specific order, maybe depending on some criterion C, e.g., the customer profile. In that case, the AND-split and -join should be replaced by the XOR-split and -join shown in Fig. 21.

Figure 10 (Option) leaves the decision to the actor. But sometimes this freedom to choose D1 should be somewhat restricted, say, only allowed when a specific condition C holds, but not otherwise. This might lead to the diagram in Fig. 22.

We note that a condition can be composite and might have various forms, e.g., like 'C_1 **or** C_2' or 'C_1 **and** C_2 **and** … **and** C_m' (so, in fact consisting of several conditions).

Figure 10 represents a 'tacit' decision. This could be turned into an explicit decision by preceding it with a question asking for an explicit decision ('Do D1?' or something equivalent); see Fig. 23 and also Fig. 18c ('Rush?'). This also makes explicit that the decision is in fact additional input.

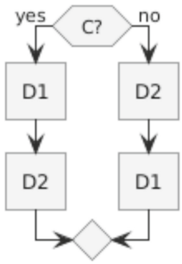


Fig. 21. Order depends on condition C

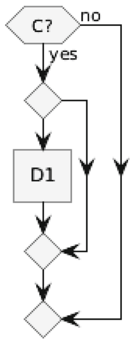


Fig. 22. Conditional freedom

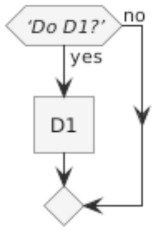


Fig. 23. Explicit decision

All 'binary' examples like the one in Fig. 24 can be treated as indicated there.

Exception possibilities can be treated with our constructs as well. For instance, if there is an exception possibility after Dk in a sequence D1, …, Dn, then the Activity Diagram can become as in Fig. 25.

So, our well-formed Activity Diagrams cover much more than just the basic constructs presented in Sect. 2.

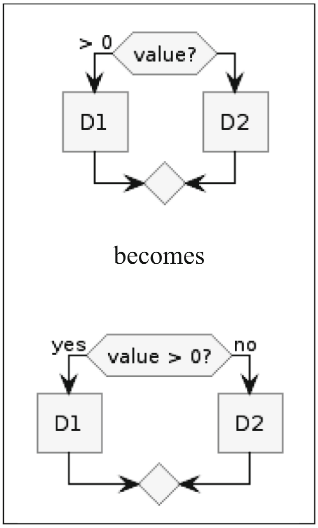


Fig. 24. Turning any binary alternative into a Boolean alternative

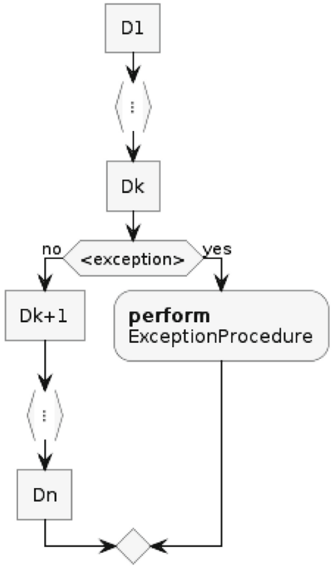


Fig. 25. Treating exception handling

7 Conclusions and Further Work

We introduced the new and general idea of an exact ‘grammar for pictures’ and worked it out. In particular, we introduced a grammar for Activity Diagrams.

By means of just a few production rules, we constructed an expressive, well-defined, well-understandable, and consistent class of constructs for Activity Diagrams, having some convenient structural properties (e.g., reachability). The paper provides a well-defined subset of Activity Diagrams within the hardly restrained class of ‘all’ Activity Diagrams (which include meaningless Activity Diagram constructs). The strength of the chosen, limited class is in its specific selection. Following the constructs of structured programming languages, our approach enhances *Structured Process Modelling*.

Because of their simplicity, our well-formed Activity Diagrams have a clear ‘control flow semantics’; we don’t need a complex ‘token-calculus’ for the flow of control.

Although it is common to present business process theories by means of examples only, we developed a general theory, not just a ‘theory-by-example’.

Further Work. We will provide an unambiguous mathematical, *declarative* semantics for our class of constructs for Activity Diagrams, treating the *statics* (states) as well as the *dynamics* (state changes), in an integrated way. The diagram constructs then have a clear semantics in terms of state changes achieved.

These issues (and our solution) are not UML-specific. Currently, we are working on something similar for BPMN, an alternative way of representing workflows graphically.

What could also be done, is extending our notion of well-formed diagrams, while still having an unambiguous mathematical, declarative semantics. E.g., we did not yet treat constructs regarding ‘time’ (such as timers and timer events). We want to work on this extension in the sequel.

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VR-SBOM: Visualization of Software Bill of Materials and Software Supply Chains in Virtual Reality

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Abstract. As software capabilities increase and are delivered more frequently, further external software components (e.g., services, frameworks, platforms, or libraries) are incorporated. Thus, organizations and IT increasingly depend on more complex and dynamic Software Supply Chains (SSCs). Yet, the entire set of components involved are often opaque for end users, businesses, and even developers. Software Bill of Materials (SBOM) formats (SPDX, CycloneDX) provide essential information regarding components, yet their voluminous text and 2D tool visualization limitations obscure the underlying models and SSC. This paper contributes an immersive Virtual Reality (VR) solution concept VR-SBOM towards holistic contextualized multi-layout visualization of SSCs with heterogeneous SBOMs. Our prototype implementation demonstrates its feasibility, while a scenarios-based case study exhibits its potential and scalability.

Keywords: Software Bill of Materials · SBOM · Software Supply Chain · Virtual Reality · Visualization · SPDX · CycloneDX

1 Introduction

Modern software development is highly dependent on external components (e.g., libraries, packages, frameworks, Web APIs), yet often unmindful of its inclusion "under the hood." A 2024 industry analysis of 20K+ enterprise applications found [1]: 180 component dependencies on average (10% having 400+), with modern commercial software consisting of up to 90% Open-Source Software (OSS) components; 6.6T+ downloads across 7M+ OSS projects/components involving 60M+ releases (averaging 16 per OSS project annually). As to deployment frequency due to Continuous Delivery (CD) automation, already in 2012 estimated average daily deployments for Google were 5.5K and Amazon 23K [2, 3]. A 2021 survey of 1200 professionals revealed elite performers (26%) were deploying on demand multiple times a day [4]. High dynamicity with more external component dependencies results in larger, more complex, and changing Software Supply Chains (SSCs). While SSC Management (SSCM) aims to plan, monitor, control, optimize, and analyze SSCs, the essential characteristics inherent in software's nature, namely complexity, conformity, changeability, and invisibility [5],

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can be transmuted to SSCs. These characteristics, in conjunction with obscured external dependencies, make SSC transparency, comprehension, and analysis a challenge, and hence their management.

A Bill of Materials (BOM) defines the material components necessary to produce a product, and can be used to assess costs, risks, supply and support aspects, etc. The associated material distribution flows and multi-stage production dependencies can be viewed as a supply chain, with each stage processing materials (goods or services) to a consumer. For product-centric businesses, modeling and analysis of supply chains are inherent and vital to the business. Applying the BOM paradigm to software acquisition/development results in a Software BOM (SBOM) utilized by a SSC, which includes the components, libraries, tools, and activities needed to develop, build, procure, provision, and/or distribute some software artifact. As the need for SSC transparency became evident to address security vulnerabilities and license conformance, a push towards SBOM formats and their adoption by software suppliers became apparent. The System Package Data Exchange (SPDX) [6] (formerly Software Package Data Exchange) SBOM format by the Linux Foundation was released in 2011 and published in 2021 as ISO/IEC 5962 [7]. OWASP's alternative SBOM format CycloneDX (CDX) [8] was published in 2018 and later as ECMA-424 [9]. As of 2023, GitHub offers an "Export SBOM" function, simplifying SBOM generation and increasing the likelihood of further SBOM adoption. Over 72K SBOM's were published by the end of 2023 [1]. Hitherto, the lack of practical and accessible SBOM information and adoption had made SSC *modeling* impractical, a prerequisite for SSCM. Current SBOM/SSC tools lack comprehensive visualization, affecting model transparency, comprehension, and analysis. This, in turn, impacts the veracity and premises of software business models that count on coherent, correct, conformant, sufficient, and resilient SSCs - often only noticed after SSC disruptions occur. SSCM necessitates models offering transparency and insights that can address software's complexity, conformity, changeability, invisibility, and external dependencies.

To address the comprehensive visualization of SBOM and SSC models, this paper proposes and investigates an immersive experience using Virtual Reality (VR). Our prior VR-related contributions in the Enterprise Architecture (EA) space include: VR-EA+TCK [10] supports EA models, integrating enterprise repositories, Atlas, IT blueprints, and knowledge and content management systems, with VR-EvoEA+BP [11] animating enterprise evolution and Business Processes (BPs). In the Software Engineering (SE) area: VR-ISA [12] enables informed software architecture, VR-SDLC [13] models development lifecycles, VR-GitCity [14] and VR-Git [15] model Git repos, VR-UML [16] for Unified Modeling Language models, and VR-DevOps [17] for CD pipeline models. This paper contributes VR-SBOM, a VR solution concept for context-enhanced multi-layout visualization of SBOMs and SSCs, supporting comprehensive visualization and inter-model SSC analysis. Our realization demonstrates its feasibility, while a scenario-based case study exhibits its potential and scalability. Furthering SSC transparency and comprehensibility enhances SSC management and optimization options.

The paper is structured as follows: Sect. 2 discusses related work; Sect. 3 presents our solution concept; Sect. 4 details our realization; our evaluation is described in Sect. 5, followed by a conclusion.

2 Related Work

Work related to the visualization of SBOMs includes Jones and Tate [18] for interactively comparing BOM graphs in 2D. DepVis [19] interactivelyto visualizes third-party dependencies and vulnerabilities in 2D. V-Achilles [20] visualizes npm package vulnerabilities for GitHub in 2D. Google's central repository Open Source Insights (OSI) [21] provides OSS package security information with 2D graph-based dependency visualization. OWASP's Dependency Track [22] is an intelligent component analysis platform for CDX files, offering a 2D dashboard with monitoring and risk analysis. OWASP CycloneDX Sunshine [23] visualizes CycloneDX files in 2D. Regarding SSC visualization, Kula et al. [24] propose a generalized model for visualizing library popularity, adoption, and diffusion via a software universe graph, library coexistence pairing heat maps, and dependents diffusion plots. We are unaware of any tools that currently offer 3D or VR-based SBOM and SSC visualization.

Aside from visualization, work related to SBOM tooling includes Mirakhorli et al. [25], who conducted an extensive empirical analysis of 84 open-source and proprietary SBOM tools to assess the current landscape, highlighting many issues including interoperability, quality, and many having a niche focus and immaturity. Yousefnezhad and Costin [26] evaluated real-world SBOM tools with regard to DevSecOps, SSC, and compliance scenarios. Wang et al.'s book on SSCM [27] surveys research literature and describes SSC modeling, analysis, issues, and techniques, yet SSC visualization is not addressed.

Hence, further work is needed to investigate (immersive) SBOM/SSC visualization concepts to support various analysis, management, and collaboration scenarios.

3 Solution Concept

Our solution approach leverages VR for visualizing one or more SBOM models and relations simultaneously, mapped to a spatial structural model that can be immersively explored and experienced in 3D.

3.1 Grounding of Our Solution Concept in VR-Related Research

To address possible reservations about the appropriateness of VR in our solution concept, our reasoning is based on prior VR research in areas we view as related to modeling, analysis, and collaboration, some of which we highlight here. In their systematic meta-analysis, Akpan & Shanker [28] showed VR and 3D offer significant advantages in the area of discrete event modeling, including model development, analysis, and Verification and Validation (V&V). Of 23 articles examining 3D analysis, 95% concluded using 3D was more potent and lead to better analysis than 2D, e.g., when evaluating a model's behavior or performing a what-if analysis. They also found a consensus that 3D/VR can present results convincingly and understandably for decision-makers. 74% of 19 papers concluded that 3D/VR significantly improves the model development task (supporting teams and improving precision and clarity). To investigate VR's suitability for analytical tasks for an information architecture, Narasimha et al. [29] used a card sorting collaboration experiment. They found that VR was at least as good as in-person card sorting, and for certain variables VR was even better than both conventional and video-based conditions. Qualitative data evaluating awareness indicated that during collaborative interaction, participants were aware of their task, others, and their context, while collaborating similarly to an in-person setting. Additionally, the qualitative data showed evidence of positive views towards VR. The outcomes suggest that both a sense of presence and collaboration (equivalent to an in-person setting) is possible within VR. A survey of Immersive Analytics (IA) by Fonnet & Prie [30] analyzed 177 papers. They found concurring evidence that for graph and spatial data analysis, IA provides benefits vs. non-IA when the scene complexity exceeds the 2D display, while for multi-dimensional data, the advantages are more task-dependent. They remark that while IA enables exploration of large-scale data worlds, context-aware navigation techniques are insufficiently exploited - although they are critical for users. We thus conclude that an immersive contextual VR experience has significant potential for comprehensively depicting large models in 3D while supporting awareness, modeling, analysis, V&V, decision support, stakeholder inclusion, and collaboration.

3.2 Relation to Our Prior VR-Related Research

Our solution map in Fig. 1 positions VR-SBOM relative to our other VR-based solutions. Besides our own prior work introduced earlier, our generalized VR Modeling Framework (VR-MF), described in [31], provides a domain-independent hypermodeling framework addressing key aspects for modeling in VR: visualization, navigation, interaction, and data. VR-EA [31] supports EA models in VR, including ArchiMate and BPMN via VR-BPMN [32]; VR-ProcessMine [33] supports process mining; VR-EAT [34] integrates and models enterprise repositories and the Atlas EA tool and blueprints. In the SE and Systems Engineering (SysE) area, there is VR-V&V [35] for V&V, VR-TestCoverage [36] for test coverage. As SBOMs/SSCs can be relevant to at least two perspectives, we position VR-SBOM as spanning two broad areas: EA & BP from the IT perspective; and SE & SysE from the software development perspective. Broad holistic solutions would be feasible in combination with our other solutions. None of our prior work has investigated the modeling of SBOM or SSCs in VR nor addressed their specific challenges.

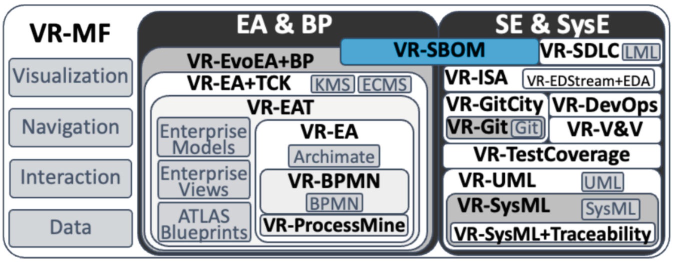

Fig. 1. VR solution concept map showing VR-SBOM (blue) in relation to our other concepts.

3.3 The VR-SBOM Solution Concept

The contribution of this paper is a VR solution concept for context-enhanced multi-layout visualization of SSCs and SBOMs. This solution concept is abstract, extensible, and independent of SBOM modeling format (SPDX, CDX). By annotating contextualized connected SBOM models, SSCs can be immersively visualized and experienced. Thus, the comprehension and analysis of SSCs becomes feasible, offering a larger picture of how various software artifacts relate to the SSC. Furthermore, accessibility, comprehension, and collaboration via concern-based (risk, resilience, security, etc.) perspectives for viewing and filtering a model for diverse stakeholders, such as software developers, enterprise architects, business analysts, quality assurance, IT administrators, security specialists, compliance auditors, or managers. These objectives are addressed as follows:

Data. A Data Hub supports flexible data integration via ports and adapters in combination with a data repository. SBOMs in both formats, CVEs, and any other SSC contextual data is integrated and stored in our JSON format. Alternatively, if data freshness is paramount, data can forego storage and be integrated live via Web APIs.

Visualization. A Directed Acyclic Graph (DAG) visualization paradigm was chosen to generically and scalably visualize extensive SBOM and SSC models. SBOM elements are represented by spherical nodes, while relations (edges) are depicted as lines. Element types are differentiated by customizable node colors displayed via a legend. Node labels provide naming information, while detailed element metadata can be retrieved via our VR-Tablet concept. Labeled glass boxes enclose models to support model orientation, differentiation, and contextualization. Multiple DAG layout options are offered: 1) a spatially-dense 3D *Sphere* (or nexus) (Fig. 2a) with node placement on the sphere's surface and all relations within, for comprehensive overview while minimizing spatial distances; 2) *Category-and-Level* (Fig. 2b) bundles nodes by type (category) on cylindrical layer surface (levels) positioned on vertical axis near layers having most relations with its type, for determining (un-)common types and relations; 3) *Force-Directed Graph* (Fig. 2c) positions nodes using attractive and repulsive forces to approximately equalize edge lengths while minimizing collisions, for ascertaining highly (dis-)connected nodes; 4) *Radial Tidy Tree* (Fig. 2d) orders nodes hierarchically along a vertical radial tree (cone-like) with ever larger lower rings, for navigating granularity and depth; 5) *Stacking Radial Tree* (shown later), like Radial Tidy Tree but stacking multiple rings within a category level, for reducing ring circumference, and 6) *Custom placement*. Thus, hitherto intangible SBOM elements and relations are flexibly visualized and graph-based visual comparisons support stakeholder concerns.

Navigation. To reduce the potential for VR sickness symptoms during immersive navigation, our solution concept supports two navigation modes: 1) locomotion gliding controls (default), enabling users to fly through the VR space and get an overview of the entire model from any angle they wish, or 2) teleporting permits a user to select a destination and be instantly placed there (i.e., moving the camera to that position), reducing movement through a virtual space.

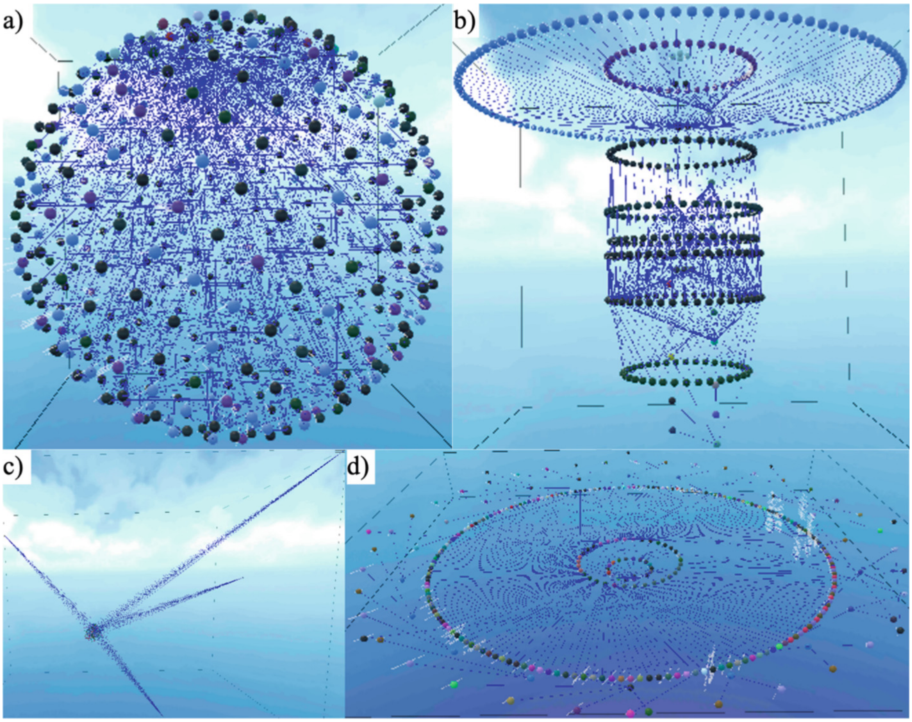

Fig. 2. Visualization layouts for an SBOM containing 448 nodes: a) Sphere/nexus, b) Category-and-Level, c) Force-directed, and d) Radial Tidy Tree.

Interaction. The VR controllers and our VR-Tablet concept support interaction. Our VR-Tablet paradigm provides: interaction support, detailed information regarding a selected element, or browsing, filtering, searching, and settings. Any browser-based (multimedia) content could also be displayed as shown in our prior work [10].

4 Realization

To determine the feasibility of our solution concept, we realized a prototype having the logical architecture in Fig. 3 and described below.

Data Integration. The Data Hub integrates and stores data in a NoSQL document-oriented local database MongoDB in JSON and offers endpoints (ports) to the VR frontend via the ASP.NET Core Web API. Adapters are used to convert SSC-relevant data in various SBOM formats such as SPDX, CDX, and non-SBOM data such as CVE data in the CVE Record Format [37]. MongoDB was used as a local database consisting of two collections, one for SBOM-specific data (SPDX, CDX, etc.) and another for non-SBOM (e.g., additional SSC) data (e.g., CVE records).

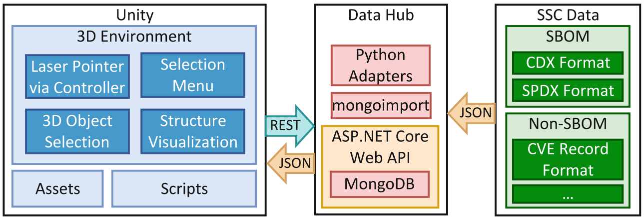

Fig. 3. VR-SBOM Logical Architecture.

Visualization. VR support was realized in C# with Unity 2022.3.21f1, accessing the Data Hub via REST (REpresentational State Transfer) and retrieving JSON data. Nodes are depicted as spheres, key-value pairs as text or as a popout tooltip, and references as lines. For directional lines, the darker (closer) end (blue/red) is the enclosing source and the lighter (aqua/pink) end the point referred to, reducing the clutter arrowheads would create while providing direction. Multiple SBOM graphs can be depicted concurrently and are labeled and contextually distinguished via boundary (transparent glass) boxes, which are labeled on the bottom by SBOM name/ID and indicate node metrics in the upper left corner (Fig. 4a). The graph layouts (Sphere, Category-and-Level, Radial Tidy Tree, Force-directed Graph, and Stacking Radial Tree) can be switched to support a different focus (Fig. 4b). For the *Sphere* (nexus) layout, all nodes are placed on the sphere's surface equidistant from each other, while all lines (connections) are inside the sphere. For *Category-and-Level*, the nodes are first segregated by category (type) and then positioned along a vertical line based on its level. For the *Radial Tidy Tree* layout, a vertical hierarchy is used with each lower-layer ring placed even further out in the x/z direction (even if the level is sparse), causing it to typically be wider than higher. In the *Force-directed Graph* layout, connected nodes receive an attractive force, while unconnected nodes receive a repelling force; the vectors are then combined to determine a node's position, causing the most highly-connected nodes to be more centric. *Stacking Radial Tree* reduces ring radius by stacking multiple rings at the same level. The implementation can be readily extended to support additional graph visualization types and store *Custom placement*. A legend of the node types and their randomly-assigned colors is placed on top of (or in proximity of) the boundary box. To reduce visual clutter, by default when nodes have the same property values, they are merged, but this can be toggled. Storing custom layout adjustments was not yet implemented due to time constraints.

Navigation. Both locomotion and teleporting are supported, including teleporting to a search result.

Interaction. Interaction is supported with our VR-Tablet. To prevent the VR-Tablet from interfering with comprehension or navigation, it is hidden and appears when the left controller is rotated outwards by about 90°. It offers a menu consisting of three tabs: Main, Search and Options, as shown in Fig. 4:

a) Main offers: a slider “Show Layers” for adjusting the maximum graph layer depth, a dropdown for desired layout type, and a scroll view of SBOM names or object IDs. In Scroll View, the selection acts as a toggle: if the SBOM is already depicted (green), then it is hidden (red), otherwise it is loaded.
b) The dropdown Graph Types offers various graph layouts (Sphere, Category-and-Level, Radial Tidy Tree, Force-Directed Graph, and Stacking Radial Tree),

Fig. 4. VR-Tablet menu showing tab sections: a) Main, b) Layout options, c) Compare Versions submenu, d) Search/Filter, e) Search Results, and f) Options.

a) “Compare Versions” submenu is offered when two graphs are selected; if checked, the SBOM node differences are highlighted as a colored ring, with green/red indicating new/missing node (can ghost rest).
b) Search offers both searching and filtering based on an input field that offers a pop-up prefab platform-independent MRTK keyboard to enter a search string. The search includes both types and values and ghosts (makes transparent) all elements not in the result set. Different search and filter types are supported: “Search Only Within Selected Type” searches nodes within type, “Search Hierarchies Filtered by Selection” to search nodes of a subgraph, and “Search Dependencies Filtered by Selection” to search dependencies of a subgraph.

Fig. 5. Selecting top left green node opens JSON position panel (bottom right) in VR-Tablet.

c) Search results are displayed in a separate extra VR-Tablet pane with scrollable search results, which may be numbered based on the hierarchy level (1 = top-level). Selecting a result offers a Tooltip to the right of the selection indicating node name, etc. Teleporting to any search result is supported.

d) Options offers these additional settings:

– "Show CVE" depicts CVE data related to a loaded SBOM as separate graphs in bounded glass boxes, with a red connection to its location in the SBOM graph.
– "Show duplicate Nodes" will depict all nodes separately, since by default all nodes with the same property values are depicted by a single node.
– "Ball Size Depending On Relation Count" will cause the node size to be larger when it has more relations relative to other nodes.
– "Enable Glow For Every Layer"
– "Comparison: Ghost Nodes with no Changes" causes unchanged nodes to be ghosted (transparent) to reduce visual clutter during comparison analysis.
– "Text Length": constrains the allowable max text length of labels.

Selecting a node will keep its node type opaque, while ghosting all other nodes of different types and lines unassociated with a node of that type. Node-specific JSON information is displayed on an additional freely movable pane, offering a dropdown list of all positions of the node in the SBOM file, as shown in Fig. 5.

The evaluation then demonstrates how these realized capabilities are utilized.

5 Evaluation

For the evaluation of our solution concept with our prototype realization, we refer to the design science method and principles [38], in particular, a viable artifact, problem relevance, and design evaluation (utility, quality, efficacy). For this, a scenario-based case study focuses on supporting SBOM and SSC comprehension, analysis, and contextualization, the scenarios being: Heterogeneous Multi-SBOM Interoperability, Comparison and Dependency Analysis, License (search/filtering) Analysis, Security and SSC Analysis, and Scalability. Further SBOM use cases can be readily mapped to these scenarios (provenance, foreign ownership, outdated components, etc.). Abbreviations referred to for the SBOM files utilized in the evaluation scenarios are given in Table 1. Further SBOMs were also tested but are not listed.

Table 1. SPDX and CDX files used in evaluation.

Name	Abbrev	Nodes (w/o duplicates)	Types	Lines	Format	Modifications
Dropwizard[1]	DW	(3038)	38	10621	CDX 2.0.2	3 CVEs linked
Acme Application[2]	AA	129(88)	21	154	SPDX 3.0	–
Acme Application New[2]	AAN	132(88)	35		SPDX 3.0	+/– 3 nodes

[1] https://github.com/CycloneDX/bom-examples/blob/master/SBOM/dropwizard-1.3.15/bom.json
[2] https://github.com/spdx/spdx-examples/blob/master/software/example13/spdx3.0/example13.spdx3.json

5.1 Multiple Heterogeneous SBOM Interoperability Scenario

To be practical, SSCs must be able to view multiple SBOMs having differing formats simultaneously. For this scenario, SBOM interoperability support is demonstrated by depicting multiple heterogeneous SBOM models, with DW based on a CDX model in the left boundary box and AA based on an SPDX model on the right in Fig. 6.

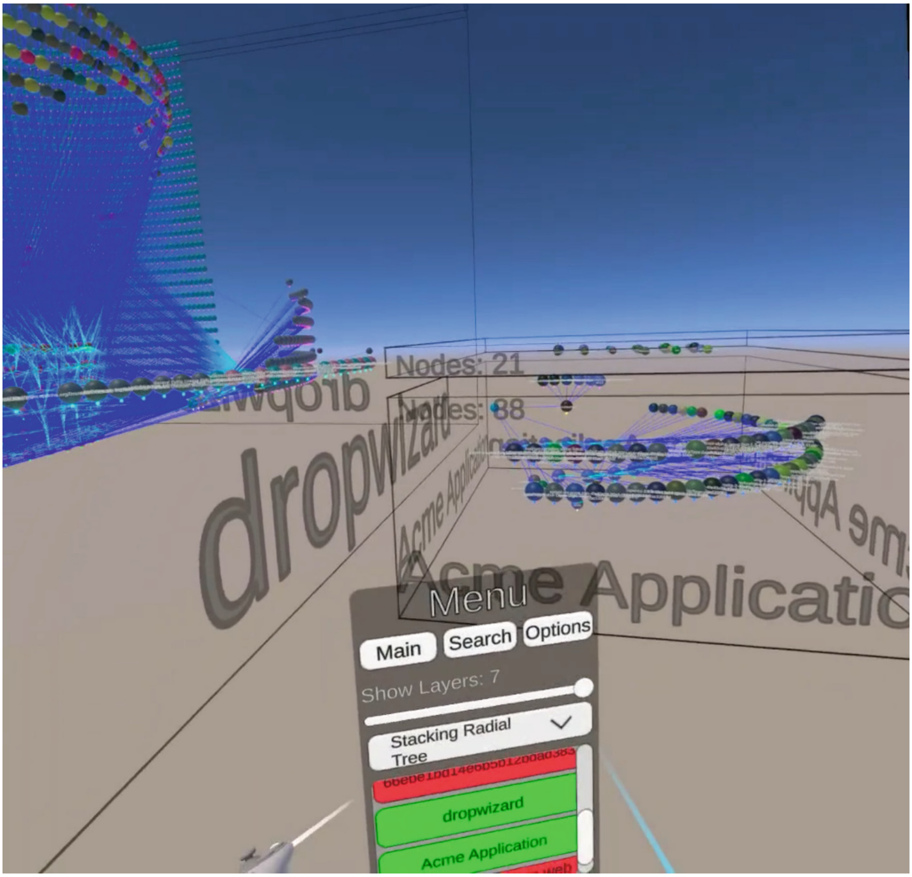

Fig. 6. Multiple heterogeneous SBOMs loaded (green) (DW CDX left, AA SPDX right).

5.2 Comparison and Dependency Analysis Scenario

This scenario demonstrates comparison analysis support via a visual delta of graphs, in particular selecting SBOM versions in VR-Tablet (Fig. 4c). As shown in Fig. 7, green rings highlight additions, red rings deletions (modifications use both). Dependency analysis is supported via node size based on relation count (Fig. 7 right) - relevant, e.g., if high relation risk is a concern. Dependency navigation is shown later.

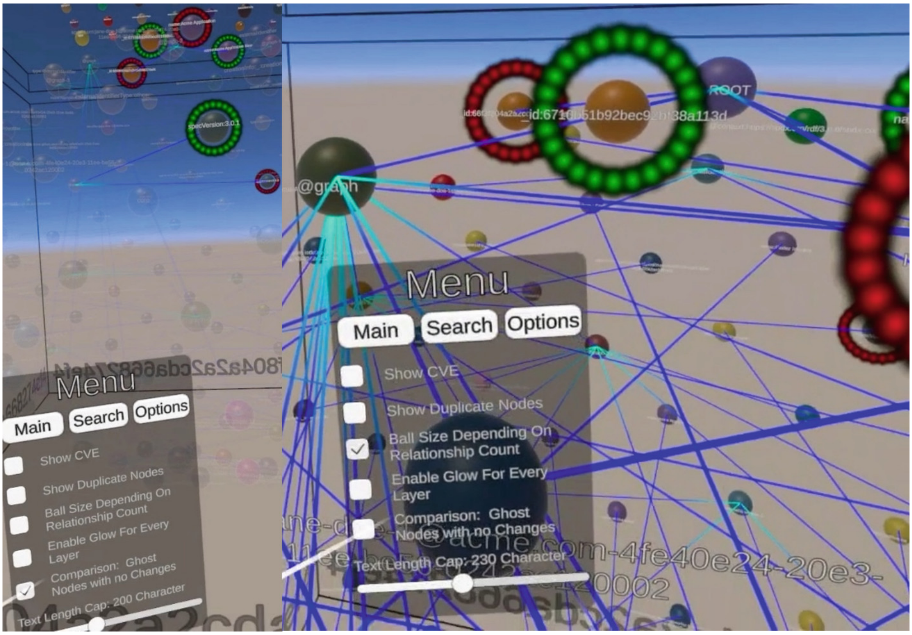

Fig. 7. AA SBOM version comparison (left) highlighting additions/deletions (green/red ring) and ghosting "Nodes with no Changes"; on right, "Ball Size Depending on Relation Count".

5.3 License (Search/Filtering) Analysis Scenario

A license analysis scenario is a typical SBOM use case. We use search and filtering capabilities to demonstrate how this scenario is supported, yet these capabilities can support further scenarios and stakeholder concerns (security, risk, compliance, etc.).

Search: A basic search finding all occurrences of a given string across all nodes.

Filtered by Type: Searching only within a certain property type, e.g., name, description, id. As shown in Fig. 8, selecting the node type "id", enabling "Search Only Within Selected Type", and providing with search string "MIT" shows a results panel listing any nodes of type "id" containing the string MIT (ghosting others). Selecting a specific search result teleports to that node, with the panel then showing that node's hierarchical path to the root node grasp its context. Hovering over any hierarchy element shows a tooltip to the right providing that node's name. Selecting a path element teleports to it. Via the top panel arrow, one can return to the previous search results to pick another.

Filtered Node Hierarchy. This type of search filter can be useful, e.g., when concerned only about a selected component or some subgraph hierarchy. Conceivable search examples include determining if some database is the open source or enterprise version, or the version of some library within a software component. For our license analysis case example in Fig. 9, "Search Hierarchies Filtered by Selection" was enabled and the "license" node selected (ghosting all nodes outside hierarchy). Then the search string

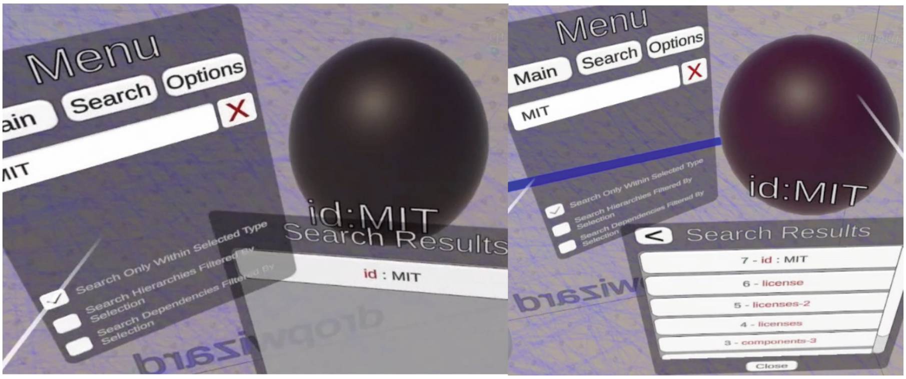

Fig. 8. Left: selecting type "id", with "Search Only Within Selected Type" for "MIT" searches all nodes of that type containing that string, providing a "Search Results" panel; selecting any search result then teleports to it, which then shows its contextual path to its root node (right).

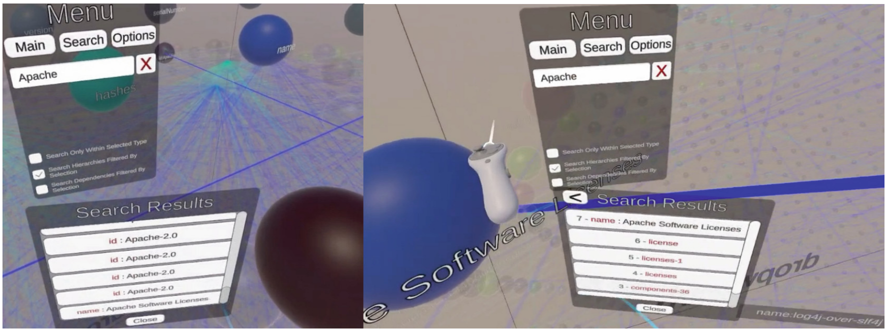

Fig. 9. Left: selecting node "license," then "Search Hierarchies Filtered by Selection" for "Apache" gives search results only within the license subhierarchy (independent of type); selecting a search result (e.g., name:) teleports to it (right), showing its contextual path to its root node; hovering on result shows tooltip with name (here the component's name is logback-core).

"Apache" is entered via the virtual keyboard, which shows the search results panel listing all matching hierarchically deeper nodes in the SBOM (ignoring any higher up or parallel hierarchies or relations). While we selected the license hierarchy here, we could have selected any component hierarchy. Selecting a search result teleports to that node, whereafter the panel shows the complete path to the root node (with tooltip support), to help contextualize it.

Filtered Dependencies: Via this search type, directly related dependencies are searched/filtered. This can find any nodes across all components as long as they directly relate to a node of interest. For our license scenario shown in Fig. 10, "Search Hierarchies Filtered by Selection" was enabled, the "license" node selected, and the search string "GNU" given via the virtual keyboard. The search results panel shows any nodes *directly related* to the node (license) containing the string "GNU" independent of its hierarchical position. Hence, no GNU components are shown that don't relate to license. Selecting

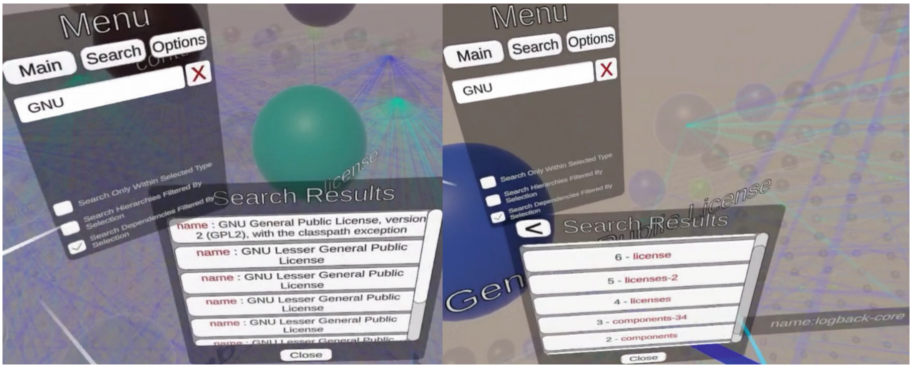

Fig. 10. Left: selecting node "license," then "Search Dependencies Filtered by Selection" for "GNU" gives search results for nodes *directly related* to "license" and containing "GNU"; selecting any search result teleports to it (right) then showing contextual path to root node; hovering on result shows tooltip that provides node name (here the component's name is log4j-over-slf4j).

any search result teleports to that node, whereafter the panel shows the complete contextual path from that node to the root node. This context hierarchy can then be explored by hovering over any result, causing a tooltip to pop out on the right that provides its element name, in our example "logback-core". Selecting an element causes one to teleport to it. The top panel arrow returns to the previous search results.

5.4 Security Analysis and SSC Analysis Scenario

SSCs necessitate chaining (linking) elements and incorporating supplementary data. While SBOMs are standardized, SSC models as such are not, yet SBOMs foresee and provide link support (e.g., via references). Both CDX (e.g., via BOM-Link, externalReferences) and SPDX (e.g., via ExternalRef) support flexible intra- or inter-linking of various type-specific data (SBOMs, models, Web APIs, documentation, etc.). Due to space constraints, as the security analysis scenario involves linking, it serves to demonstrate support for both analysis cases; linking non-SBOM CVE vulnerability models can represent linking to any extrinsic data/models for an SSC. In this case, the original DW SBOM was modified to fictionally link three extrinsic CVE JSON records from CVE List Downloads [39], consisting of two general ones (CVE-2020-11002 and CVE-2020-5245) and one specific to the Log4j component (CVE-2021-44228), as shown in Fig. 11. Each CVE record model was placed in its own boundary box linked via red lines to applicable SBOMs (Fig. 12, Fig. 13 left). Selecting any "CVE" search result shows its context path (Fig. 13 right), which can be used for teleporting to get more detailed (CVE) data. The CVE references demonstrate how other references to data/models could be included to support SSCs and their analysis.

```
{
  "type": "library",
  "bom-ref": "pkg:maven/org.slf4j/log4j-over-slf4j@1.7.26?type=jar",
  "publisher": "QOS.ch",
  "group": "org.slf4j",
  "name": "log4j-over-slf4j",
  "version": "1.7.26",
  "description": "Log4j implemented over SLF4J",
  "hashes": [
  ],
  "licenses": [{"license": {
    "name": "Apache Software Licenses",
    "url": "http://www.apache.org/licenses/LICENSE-2.0.txt"
  }}],
  "purl": "pkg:maven/org.slf4j/log4j-over-slf4j@1.7.26?type=jar",
  "externalReferences": [
    {
      "type": "website",
      "url": "http://www.qos.ch"
    },
    {
      "type": "distribution",
      "url": "https://oss.sonatype.org/service/local/staging/deploy/maven2/"
    },
    {
      "type": "vcs",
      "url": "https://github.com/qos-ch/slf4j"
    }
  ],
  "vulnerabilities": [
    "CVE-2021-44228"
  ]
},
```

```
{
  "bomFormat": "CycloneDX",
  "specVersion": "1.2",
  "serialNumber": "urn:uuid:b4
  "version": 1,
  "metadata": {…
  },
  "components": […
  ],
  "dependencies": […
  ],
  "name": "dropwizard",
  "vulnerabilities": [
    "CVE-2020-11002",
    "CVE-2020-5245"
  ]
}
```

Fig. 11. SBOM modifications to DW CDX linking CVE vulnerabilities: CVE-2021-44228 specific to component library log4j and two additional CVEs appended to entire library bundle.

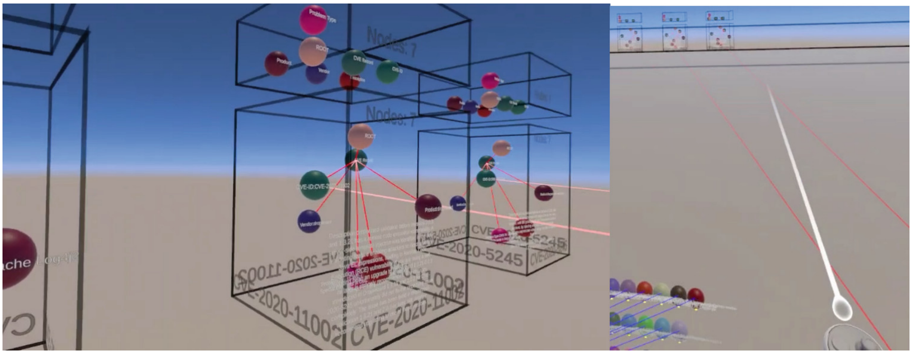

Fig. 12. Left: three juxtaposed CVEs boxes; Right: inter-relations (red) with SBOM shown.

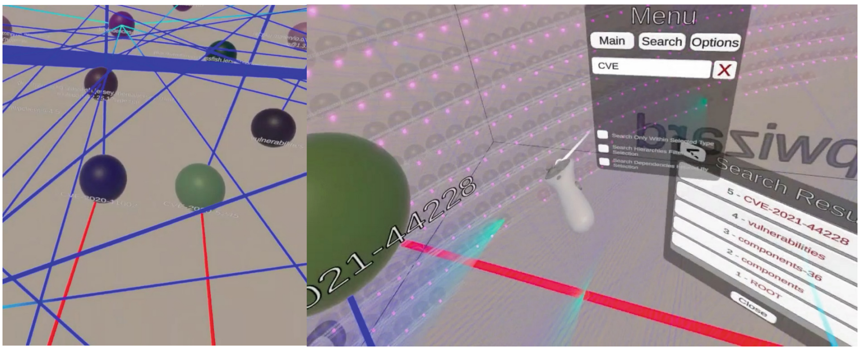

Fig. 13. CVEs-SBOMs inter-linked via red lines (left); CVE search result context (right).

5.5 Scalability Scenario

To evaluate visualization scalability, we depict SBOMs of varying sizes and layouts, each supporting a different stakeholder focus. The DW SBOM has 3038 non-duplicated nodes, 38 types, and 7 layers of depth. It is displayed as a Sphere (compact nexus) and Stacking Radial Tree (hierarchically-stacked) layouts in Fig. 14. The smaller AA SBOM is shown with Category-and-Level (type-bundled) and Force-directed Graph (dependency-centric) layouts in Fig. 15. To support comprehension at scale, the Limit Layers slider reduces unwanted layer depth, while layer glows (cubes) support layer orientation when navigating large models (especially when ghosting), as shown with AA SBOM in Fig. 16. Adjusting the Text Length slider would reduce text label clutter.

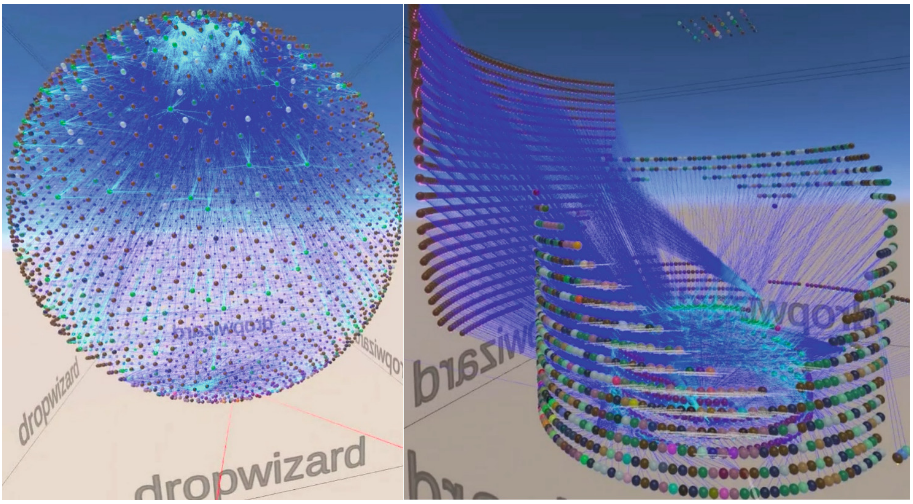

Fig. 14. Large DW SBOM as a Sphere (left) and Stacking Radial Tree (right).

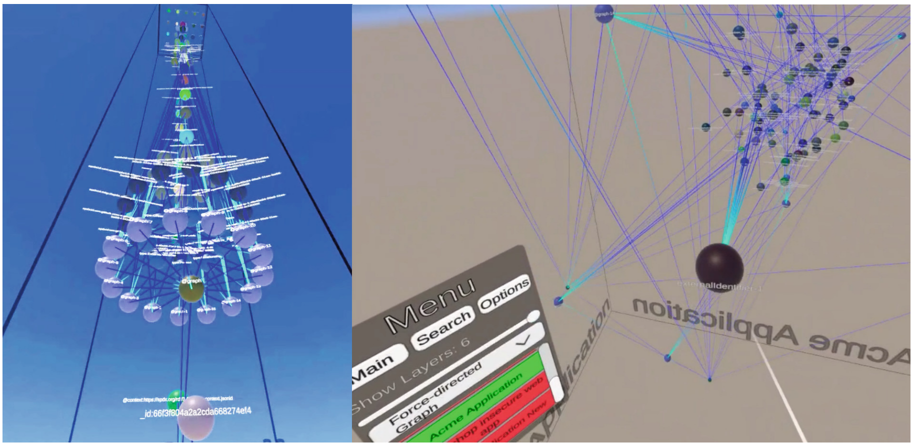

Fig. 15. AA SBOM as Category-and-Level (left) and Force-directed Graph (right).

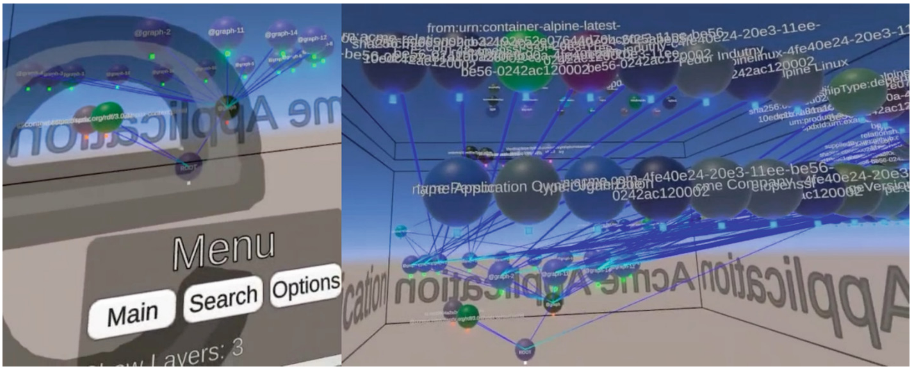

Fig. 16. AA SBOM in Radial Tidy Tree layout with Limit Layers slider on 3 (left) and without a Layer Limit (right). The colored layer glows support layer orientation. (Color figure online)

5.6 Discussion

VR-SBOM supports various SBOM visual analysis scenarios immersively, scalably, and flexibly. In contrast, current 2D SBOM visualization tools offer limited graph layout visualizations. VR offers the ability to more readily comprehend the full extent of large SSC or SBOM models, while exploring relations using various graph layout structures. SBOM models can be concurrently analyzed and SSC issues collaboratively discussed with stakeholders. Also, substructures and (unexpected or undesired) patterns within the data may be more readily evident versus extensive textual formats.

6 Conclusion

VR-SBOM contributes an immersive VR solution concept for context-enhanced multi-layout visualization of SBOMs and SSCs. Its comprehensive visualization supports both intra- and inter-model SSC analysis, portraying multiple SBOM models concurrently with contextual enhancement. Our implementation demonstrated its feasibility. The evaluation, based on a case study using SPDX/CDX models, showed its support for various scenarios: Heterogeneous Multi-SBOM Interoperability, Comparison and Dependency Analysis, License (Search/Filtering) Analysis, Security and SSC Analysis, and Scalability. Its immersive experience and space further SSC transparency and comprehensibility in a readily accessible and intuitive way, supporting SSC management, optimization, and stakeholder collaboration. Further, a combination with our other prior VR work in the EA/SE areas offers the potential for to gain more holistic insights and assess risks and opportunities for all who depend on software and SSCs.

Future work includes: realizing support for further SPDX profiles, CDX xBOM capabilities, highlighting relational differences, and a comprehensive empirical study.

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The Effectiveness of 3D Virtual Environments for BPMN Teaching: A *Quasi*-Experimental Study

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Abstract. Traditional Business Process Model and Notation (BPMN) diagrams, being static and highly abstract, often hinder comprehension, particularly for novice designers and students. This can lead to misinterpretations and process inefficiencies. In this study, we investigate whether immersive three-dimensional (3D) virtual environments can enhance the understanding of BPMN models. We developed a virtual reality (VR)-based BPMN visualization tool and conducted a *quasi*-experiment with 48 academic and professional participants, who interacted with a 3D BPMN model using Google Cardboard and a joystick. Participants completed comprehension tasks before and after the VR experience. The results show significant improvements in understanding and engagement, suggesting that immersive virtual reality can be a valuable educational tool for BPMN learning. This study contributes empirical evidence supporting the integration of 3D environments in process modeling education, offering benefits for both academic and professional training.

Keywords: Business Process Modeling · Virtual Reality · Immersive 3D Environments · Process Education · Interactive Learning

1 Introduction

Effective business process modeling is essential for promoting organizational efficiency, enabling system integration, and supporting transparency in operations. Among the available modeling notations, the Business Process Model and Notation (BPMN) has emerged as the de facto standard due to its expressive capabilities and widespread adoption across both academic and industrial contexts [19,20]. However, despite its broad acceptance, BPMN diagrams are often abstract and static, which hinders comprehension, especially among novice modelers and students [20]. These limitations can lead to misinterpretations, a focus on irrelevant details, and suboptimal modeling outcomes.

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One of the core challenges in BPMN education is the development of abstraction skills, which are crucial for learners to identify essential process elements and ignore non-essential details [19]. Unfortunately, many students and early-career professionals struggle with abstraction, often resulting in poor conceptual understanding and limited real-world applicability [4]. This highlights a broader inadequacy in traditional teaching methods, which frequently fail to promote deep comprehension of process dynamics such as token flow, execution paths, and gateway semantics.

In this context, innovative technologies like virtual reality (VR) have shown promise in supporting BPMN learning. VR provides immersive, interactive environments that stimulate engagement and enable spatial reasoning, potentially enhancing both abstraction and critical thinking skills [7,11,14,18]. The use of 3D virtual environments has also been associated with increased learner motivation and knowledge retention [3,13].

Despite growing interest in immersive learning, research on VR in business process modeling education is still emerging [16]. Few studies have empirically investigated whether 3D environments can concretely improve BPMN comprehension, particularly among learners with limited experience.

This study addresses this gap by exploring whether a 3D virtual environment can improve BPMN understanding. We developed an immersive BPMN learning environment and conducted a *quasi*-experiment involving 48 participants—students and professionals—with varying levels of modeling expertise. Participants interacted with the 3D environment using Google Cardboard headsets and joysticks and were evaluated through pre- and post-experiment comprehension tasks.

Our goal is to examine the extent to which immersive visualization reduces cognitive load, supports abstraction, and enhances the overall comprehension of BPMN models. This research contributes empirical evidence regarding the effectiveness of 3D virtual environments for BPMN education and offers insights into their potential integration into both academic and professional training contexts.

The remainder of this paper is structured as follows. Section 2 provides the theoretical background, introducing key concepts related to business process modeling and virtual reality. Section 3 reviews related studies that explore immersive technologies in process modeling education. Section 4 describes the *quasi*-experimental research design, including its objectives, hypotheses, and methodological procedures. Section 5 details the experiment's operation, including preparation, execution, and participant engagement. Section 6 presents the analysis of the results, supported by both quantitative and qualitative data. Section 7 discusses the main threats to validity and the strategies employed to mitigate them. Finally, Sect. 8 concludes the paper by summarizing the main findings and suggesting directions for future research.

2 Background

This section provides a foundational understanding of the key concepts underpinning this study. It begins by defining business process modeling and concludes with an overview of virtual reality, both of which are essential to the discussion that follows.

2.1 Business Process Modeling

Business process modeling uses various notations with distinct elements and levels of expressiveness, all adhering to a control flow structure represented as a directed graph. This graph consists of nodes (*Activities*, *Events*, *Gateways*) and edges (*SequenceFlows*) connecting them [21].

Activities can be atomic (human or automated tasks) or complex (*Subprocesses*, which are subgraphs of the model). *Events* represent occurrences impacting the process flow without specific duration, such as document updates or message receipt. *Gateways* control the flow by managing *SequenceFlow* operational convergence or divergence, without affecting metrics. The primary *Gateway* types are exclusive, inclusive, parallel, and event-based [21].

SequenceFlows defines the execution order of *FlowNodes* [21]. This study focuses on BPMN due to its standardization and widespread adoption in both research and industry.

2.2 Virtual Reality

Virtual Reality (VR) emerged from the 1938 work of Antonin Artaud and gained prominence in the 1960s, with the term becoming widely used in the 1980s Khan, 2011. VR refers to an interactive, computer-generated environment offering users an immersive experience and a sense of presence in a simulated world [2,3].

A Virtual Environment (VE) is a 3D space where users interact with digital objects or avatars, with immersion dependent on factors like lighting, geometry, and textures. High immersion occurs with multisensory devices (*e.g.*, headsets, haptic feedback), while lower immersion occurs in non-immersive setups, like desktop displays [3].

Feedback is essential in VR, enabling users to perceive their actions in the VE, enhancing engagement. Interactivity allows users to navigate, manipulate objects, and perform tasks. VR participants are categorized into novices, experts, and occasional users, each requiring different levels of support [17].

This study explores the intersection of VR and business process modeling to enhance educational strategies and outcomes.

3 Related Works

The integration of virtual reality (VR) in education has gained increasing attention, with studies highlighting its potential to enhance learning through engagement and immersion [13]. The Social Presence Theory explains how immersion in virtual environments improves learners' sense of interaction, promoting deeper learning [3]. However, research on VR in teaching Business Process Management (BPM) is still emerging. Initial studies suggest VR could significantly aid comprehension of process models, especially for beginners struggling with abstract concepts [16,19]. Despite this promise, gaps remain regarding VR's effectiveness across educational contexts and its impact on learning outcomes. This research addresses these gaps by exploring immersive 3D environments for teaching BPMN, a standard in process modeling.

Previous studies [8–10,15] have explored 3D virtual environments for BPM education, focusing on process discovery, analysis, and redesign. For instance, Aysolmaz *et al.*. [9] developed a 3D office simulation for process training, using activity patterns to link abstract models to real-world tasks. Similarly, Leyer *et al.* [15] found that 3D environments enhanced both cognitive performance and learner engagement compared to traditional 2D models. Other studies, such as those by Nkhoma *et al.* [8] and Pavaloiu [12], explored simulation games in BPM education, highlighting the benefits of real-time feedback and interactive learning environments for skills development.

Despite these advancements, there is a lack of research on how 3D environments address specific BPM education challenges, such as abstract thinking or tailoring to diverse learning styles. This study aims to bridge these gaps by examining the role of immersive 3D environments in enhancing BPM education, with a focus on abstract thinking, engagement, and knowledge retention.

4 Research Method

This study employed a *quasi*-experimental research design, a methodological approach used when random assignment of participants to groups is impractical [1]. *Quasi*-experiments are particularly valuable in applied research settings, as they generate robust and actionable insights even in the absence of full experimental control [22]. In this investigation, participants engaged in comprehension tasks after interacting with a 3D BPMN process model within a VR environment designed to enhance user interaction and learning.

The primary objective of this study was to evaluate whether a 3D VE could improve the understanding of BPMN process models, particularly among individuals with limited prior exposure to process modeling. More specifically, the study aimed to assess the cognitive impact of immersive 3D environments on process model comprehension when compared to traditional 2D representations. By doing so, this research addresses a critical gap in the literature, providing empirical evidence on the role of 3D visualization in BPMN learning.

This study qualifies as a *quasi*-experiment due to the non-random selection of participants [22]. Participants were chosen based on predefined criteria, specifically their minimal prior knowledge of BPMN, ensuring that their comprehension improvements could be attributed to the experimental intervention. While the lack of randomization limits certain causal inferences, it does not compromise the methodological rigor of the study. Rather, it aligns with the constraints commonly encountered in educational research, where complete experimental control is often impractical.

The *quasi*-experimental design followed a structured sequence of phases to ensure systematic data collection and analysis:

1. **Scope Definition**: The research problem, objectives, and goals were clearly articulated. This phase established the study framework, focusing on the potential influence of a 3D VE on BPMN comprehension.
2. **Planning**: The experiment's design was finalized, instrumentation for data collection was determined, and potential threats to validity were identified. This phase also included strategies to mitigate biases and confounding variables.
3. **Execution**: Participants interacted with the 3D BPMN process model within the VE, followed by a series of comprehension tasks to assess their understanding.
4. **Analysis**: A systematic evaluation of the collected data was conducted, integrating both quantitative and qualitative assessments to derive meaningful conclusions.
5. **Presentation of Results**: Findings were synthesized and reported, offering insights into the effectiveness of 3D environments in BPMN education.

Although these activities followed a logical sequence, the research process was inherently iterative. Adjustments were made throughout the study in response to emerging insights, enhancing its overall validity and reliability.

4.1 Scope and Setting

The study was conducted in a controlled academic environment with 48 participants, primarily recent graduates in Information Systems and Management. The experimental setup included Google Cardboard VR glasses (Fig. 1-A), an R1 Bluetooth 4.0 mini joystick (Fig. 1-B), and an Android smartphone running version 9. Participants navigated a 3D BPMN model simulating a real-world process (Fig. 1-C).

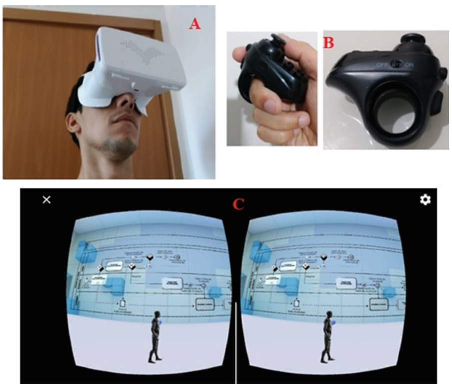

Fig. 1. Used tools.

The 3D VE adhered to BPMN standards, incorporating essential modeling elements such as activities, events, gateways, sequence flows, and tokens. The interface was designed for intuitive interaction, enabling participants to control an avatar and observe token movements, thereby fostering an engaging learning experience and enhancing stakeholder communication.

4.2 Planning

The planning phase established the experimental context and research hypotheses, ensuring methodological rigor. The key aspects included:

- **Context Selection** – The study was conducted in a laboratory setting within an academic institution, rather than an industrial environment.
- **Participant Selection** – A convenience sampling approach was adopted, ensuring accessibility while acknowledging its limitations in terms of generalizability. Participants provided informed consent and completed a sociocultural questionnaire to capture demographic and experiential data.
- **Pre-Experiment Training** – To familiarize participants with BPMN concepts, a preliminary task involved analyzing a 2D BPMN model (Fig. 2), introducing token-based process flow before transitioning to the 3D VE.

Hypotheses Formulation. The experiment was guided by the following hypotheses:

- **Null Hypothesis (H_0)**: The use of a 3D environment has no significant effect on BPMN process model comprehension.
- **Alternative Hypothesis (H_1)**: The use of a 3D environment significantly enhances BPMN process model comprehension.

These hypotheses provided a structured framework for assessing the impact of the 3D VE on learning outcomes.

Variable Selection. Following Wohlin *et al.* [22], the study identified and operationalized key variables:

- **Independent variables**: The type of visualization (3D VE *vs.* traditional 2D representation).
- **Dependent variables**: Participants' comprehension of BPMN models, assessed through structured tasks and questionnaires.

With the introduction of a third dimension, the primary dependent variable was participants' comprehension of BPMN models. The independent variable in this case was the 3D environment itself, hypothesized to enhance understanding compared to traditional 2D representations.

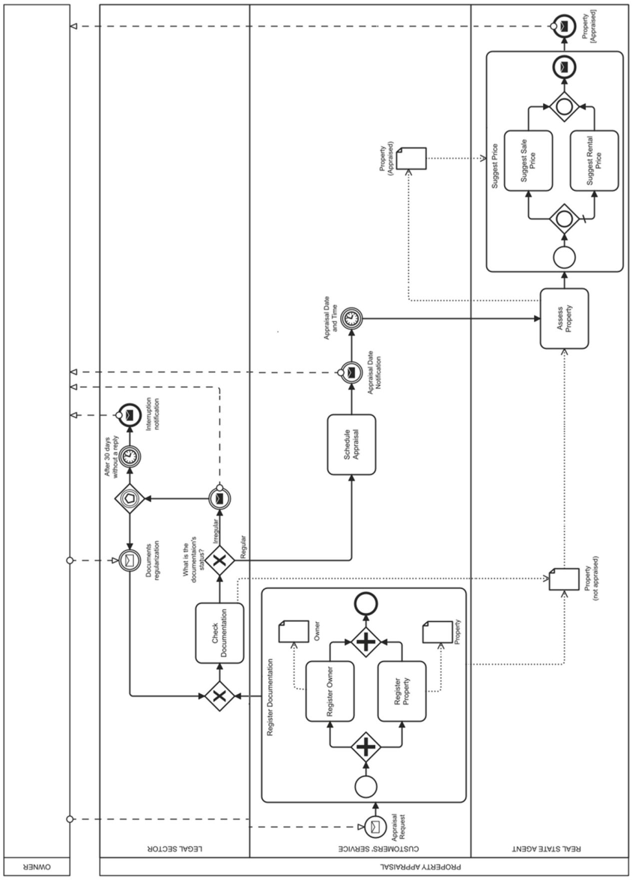

Fig. 2. Property Appraisal Process Model.

Experimental Procedure. Participants were equipped with VR glasses and a joystick (Figs. 1-A and 1-B) to interact with the 3D BPMN model. They controlled a token navigating through process flows, observing interactions between BPMN elements in real time. This gamified approach resembled a board game, offering an engaging and intuitive learning experience aligned with BPMN syntax and semantics.

Upon completing their interaction, participants answered a post-experiment questionnaire designed to capture qualitative and quantitative insights into their cognitive responses to the 3D BPMN model.

5 Operation

The operation phase of the *quasi*-experiment was structured into two main stages: preparation and execution.

5.1 Preparation Stage

The preparation stage focused on organizing participants and ensuring that all necessary materials were properly set up. This included configuring data collection instruments and sanitizing experimental equipment. Additionally, strict COVID-19 safety protocols were followed to protect all individuals involved.

Once the preparations were complete, participants received a detailed briefing on the study's objectives, followed by the informed consent process. The consent protocol was adapted from Runeson *et al.* [6] to ensure that participants fully understood the voluntary nature of their involvement and the anonymity of their data. After reviewing and signing the consent form, participants attended a 15-minute tutorial, delivered by one of the researchers. This tutorial was their only source of instruction regarding the experimental tools and procedures.

This structured approach facilitated a smooth transition to the execution stage, minimizing disruptions and ensuring consistency across participants' experiences.

5.2 Execution Stage

During the execution stage, participants engaged with a token-based navigation system in a 3D immersive environment, allowing them to interact with a BPMN model in real time. Using a joystick and 3D glasses, they controlled the movement of a token, dynamically exploring the process model.

Upon completing the interaction, participants responded to structured questionnaires designed to capture both quantitative and qualitative data regarding their experiences and perceptions. These questionnaires played a critical role in assessing the impact of the 3D environment on BPMN model comprehension.

To ensure the reliability of the findings, rigorous quality control measures were implemented throughout the execution phase. These measures included standardizing participants' interactions with the experimental tools, maintaining uniform data collection conditions, and verifying the accuracy of recorded responses. Such precautions were essential for ensuring the validity of the study, particularly in evaluating how participants engaged with the 3D models and interpreted the process flows.

5.3 Participant Anonymity and Ethical Considerations

Figure 3 illustrates the operation phase, highlighting the participation of four individuals: a recent graduate (Fig. 3-A), a postgraduate student (Fig. 3-C), and two professionals with varying levels of experience in process modeling. Among the professionals, one had limited experience (Fig. 3-B), while the other was highly experienced and held multiple certifications in process modeling (Fig. 3-D).

Although all participants provided written consent, their anonymity was preserved through the use of masks and 3D glasses, ensuring that they could not be visually identified.

By rigorously addressing both logistical and ethical dimensions, this study adhered to the highest standards of research integrity and participant safety.

Fig. 3. Some Participants Performing the Experiment.

6 Analysis and Interpretation

Beyond presenting the results, it is crucial to engage in a comprehensive discussion to interpret the findings within the study's context. This analysis is based on responses from the pre- and post-test questionnaires, aiming to assess the reliability of the collected data and the impact of using a 3D environment to enhance the comprehension of BPMN process models.

A qualitative assessment of the questionnaire responses reveals that participants generally reported a positive experience with the 3D environment. Those with prior experience in business process modeling (BPM) described the environment as immersive and intuitive, facilitating their ability to visualize and interact with BPMN model elements. Many participants highlighted that the 3D environment improved their understanding of abstract concepts and contributed to the development of critical thinking skills.

6.1 Sociocultural Questionnaire (Before the Experiment)

Of the more than 100 individuals contacted, 48 participated in the experiment, categorized into two distinct groups: academic and professional (Fig. 4 illustrates this distribution).

The study sought to examine participants' prior exposure to process modeling. Professionals were asked about their years of experience in process modeling, while academics were questioned regarding the number of courses they had

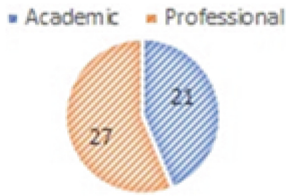

Fig. 4. Participant Groups.

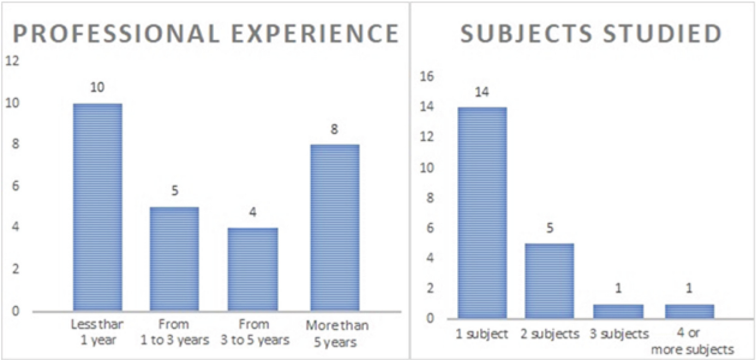

Fig. 5. Process Modeling Experience.

completed that covered process modeling concepts. The results are presented in Fig. 5.

Regarding participants' learning methods, Fig. 6 shows that the majority (24 participants) had learned process modeling through traditional instructional methods. However, reflecting a shift potentially influenced by the COVID-19 pandemic, 23 participants reported a hybrid learning experience. A deeper analysis indicated that professionals with more than five years of industry experience predominantly had traditional educational backgrounds. Interestingly, none of the participants had prior experience using 3D glasses for learning, underscoring the innovative nature of this approach to process modeling.

In terms of BPMN knowledge (Fig. 7), ten participants rated their proficiency as high, eight of whom had over five years of professional experience. Conversely, those who assessed their knowledge as low included 15 academics and 9 professionals, all of whom had less than one year of experience.

Regarding prior exposure to 3D glasses, the majority of participants (34) reported some experience with the technology. However, none had used it specifically for learning process modeling. Their prior exposure was primarily linked to digital gaming and audiovisual media, such as cinema. Additionally, 14 participants encountered 3D glasses for the first time during this experiment. To facilitate their interaction with the technology, a brief tutorial was provided.

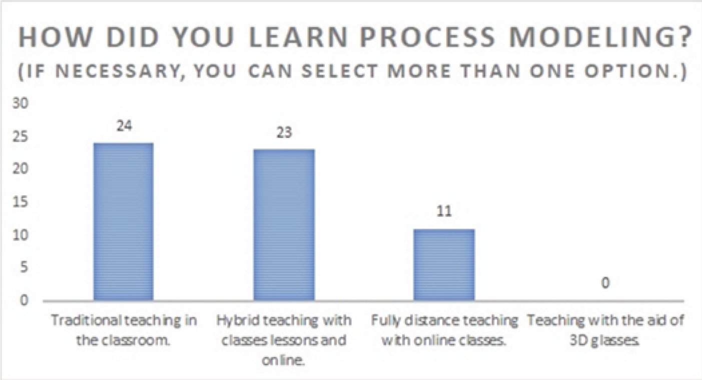

Fig. 6. Learning in Process Modeling.

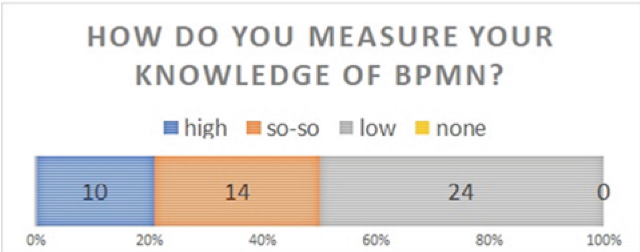

Fig. 7. Level of Knowledge in BPMN.

6.2 Second Questionnaire (After the Experiment)

The primary objective of the study was to assess whether a 3D virtual environment (VE) improves the comprehension of process models. When asked whether they could identify process execution through tokens in the VE, most of the 46 participants responded affirmatively. However, when questioned about their prior knowledge of tokens—an essential element for tracking process execution—33 participants, including 8 professionals, admitted to being unfamiliar with the concept. This finding highlights a significant knowledge gap that the 3D environment may help bridge.

After observing the token movement within the process, nearly all participants (47), including those already familiar with the concept, expressed interest in learning process modeling through the 3D environment. This feedback suggests that the 3D approach is both feasible and effective in enhancing the learning experience.

Nevertheless, one participant, despite enjoying the 3D interaction, struggled to visualize the token movement due to myopia and astigmatism, indicating that visual impairments may influence the usability of the environment. However, among the 26 participants who reported some form of visual impairment, only this individual experienced difficulty perceiving the token movement.

6.3 Qualitative Analysis

Participants responses were overwhelmingly positive, showcasing the 3D environment's capacity to enhance learning through clearer visualization and interactive engagement. Below are some key insights from participants with over five years of professional experience:

- Participant 36: "*I was able to visualize all the possibilities that the process can go through.*".
- Participant 34: "*I believe that everything that leads the user to have more interactivity facilitates learning.*".
- Participant 26: "*This environment gives greater dynamism to the interpretation of the process flow, in addition to offering a broader perspective of the process.*".
- Participant 24: "*I loved visualizing the token walking along the path. This enables a better understanding of the model step-by-step.*".
- Participant 23: "*It facilitates learning, gives more clarity in understanding the process.*".

Most experienced participants highlighted the interaction with the token and process paths as significant enhancements in the learning process. Participants with 1 to 3 years of experience offered similar praise:

- Participant 41: "*This environment leaves no doubt in understanding. When there is greater interaction with the model, it becomes easier to understand.*".
- Participant 45: "*It is possible to contextualize the model spatially. Having a view where you can navigate, go back and forth, the flow makes it much easier to understand where a process starts and ends.*".
- Participant 30: "*When you have a clearer direction, learning is also facilitated.*".

Participants with only academic experience echoed these sentiments:

- Participant 1: "*It makes understanding the process much more lucid, as well as allowing you to explore the various possibilities and their results.*".
- Participant 8: "*It brought much more clarity in understanding the model.*".
- Participant 13: "*This environment can reduce doubts about the process, in addition to having a greater dimension of positioning, enabling improvements in the process.*".
- Participant 44: "*I managed to be guided by building knowledge more assertively, without deviating from the objective of the process. I thought it was really good!*".

Participants were also asked if they would consider using a 3D environment like this in a professional setting. Here too, the responses were positive, regardless of participants' levels of experience:

- Participant 4: "*Of course I would, because it improves the visualization of processes at all levels.*".
- Participant 23: "*I would use it because this environment is more interactive and facilitates knowledge of the process. I think all employees will feel more motivated and engaged in this modeling step.*".
- Participant 24: "*I would use it because I believe it helps in understanding the process. Being able to follow the activities, actors and possibilities of the process in this way is much more interesting than just presenting it on paper or on a computer screen.*".
- Participant 26: "*I would use it because it makes the experience with interaction in the process alive, allowing the various stakeholders associated with the process to contribute to improving the process.*".

Participants with 1 to 3 years of experience similarly recognized the potential of the 3D environment:

- Participant 45: "*It greatly reduced the cognitive load for understanding complex processes, and more contextualized sub-processes. Without a doubt I would use it!*".
- Participant 48: "*This tool would be perfect to combine with another one we have and make the company's processes more present and attractive for employees.*".
- Participant 30: "*I believe that the understanding of everyone in the company would be more efficient.*".

Even participants without professional experience expressed similar views, emphasizing the value of the 3D environment in aiding collective understanding:

- Participant 1: "*It would make it more dynamic and explanatory, helping all employees to have the same vision of the process in a visual and rich way.*".
- Participant 13: "*I would use it because it makes it easier for all stakeholders to understand the business idea.*".
- Participant 17: "*I think it would be very useful because it would clarify the responsibility of each sector for their respective tasks/activities.*".
- Participant 19: "*I would use it because the dynamism and ease of reading the processes that the tool brings, would help the most novice people in the subject to easily understand the flows and paths to follow given the conditions of each activity.*".
- Participant 28: "*I believe that when we show the process in practice, or at least close to its reality, it becomes easier to understand. Of course, I would!*".

6.4 Hypotheses Analysis and Considerations

To assess the study's hypotheses, a detailed comparative analysis of the data was conducted. The results strongly support the alternative hypothesis (H_1), which posits that a 3D environment enhances the comprehension of BPMN process models. The overwhelming consensus among participants indicates that the immersive environment significantly improves learning outcomes, leading to the rejection of the null hypothesis (H_0). The introduction of a third dimension in process modeling instruction has proven to be more effective than traditional two-dimensional methods, offering a richer and more interactive learning experience.

Participants' feedback provides further insights into the efficacy of the 3D environment. Even those who initially struggled with visualizing the token movement in process flows reported that the immersive experience facilitated their understanding. Responses from both students and professionals reinforced the environment's ability to enhance clarity and engagement in process modeling. Professionals, in particular, emphasized its applicability in both educational and workplace settings.

These findings highlight the potential of immersive 3D environments in BPMN instruction, demonstrating their educational and practical benefits for improving comprehension of complex process models. Future research should investigate the long-term retention of knowledge acquired through 3D learning and its implications for professional practice.

7 Validity Threats and Mitigation Strategies

Although the results of this study are promising, there are limitations that may affect its validity. The small sample size, consisting of only 48 participants, primarily recent graduates and postgraduate students, limits the generalizability of the findings, as the sample lacks diversity in terms of undergraduate students. Expanding the sample in future research could enhance the external validity of the results. Furthermore, the *quasi*-experimental design, while useful, restricts causal inference due to the lack of randomization and limited control over external variables, such as prior exposure to BPMN and individual motivation. More rigorous experimental designs, such as randomized trials, could provide stronger causal evidence.

The data collection methods, based on questionnaires and performance tests, effectively captured quantitative aspects but may not fully reflect participant engagement and emotional responses. Incorporating qualitative approaches, such as interviews and focus groups, could offer deeper insights into the immersive experience. Another constraint is the study's focus on a specific 3D BPMN environment, which limits its applicability to other VR platforms. Future studies should explore a broader range of immersive technologies to assess their effectiveness in diverse educational contexts.

Some objections may arise regarding the novelty of the 3D environment, as prior research has explored similar applications in BPM education [5,16]. Additionally, the complexity of the VR environment and its learning curve may have influenced participant engagement and outcomes.

To mitigate these validity threats, several strategies were employed. Participants were selected based on prior BPM experience, although self-reported expertise introduces potential bias. The study was conducted over multiple days, with instructions to avoid discussion, though some external influence may have occurred. No time limits were imposed on VR usage, preserving an exploratory approach but preventing time-based learning analysis. A standardized protocol was applied to introduce participants to the VR equipment, minimizing disparities in familiarity. Although the sample size is limited, it aligns with norms in software engineering research; increasing it in future studies would improve statistical power. The lead researcher's direct involvement ensured technical reliability but introduced potential bias, which could be mitigated in future studies through independent observers. Finally, to prevent participant fatigue, interactions with the 3D models were limited, though future research could explore the impact of extended exposure.

By acknowledging these limitations and adopting mitigation strategies, this study provides a solid foundation for future research, which should aim for larger samples, more rigorous methodologies, and the exploration of a broader range of immersive technologies.

8 Conclusions

Traditional approaches to teaching BPMN often struggle to convey the dynamic behavior and structural complexity inherent in business process models. These challenges are particularly evident among novice learners, who frequently encounter difficulties in understanding abstract concepts such as token flow, control logic, and execution paths. This study investigated the use of an immersive 3D VE as a pedagogical tool to enhance BPMN comprehension.

Through the development and deployment of a custom 3D BPMN learning platform, we conducted a *quasi*-experiment involving 48 participants with diverse academic and professional backgrounds. Participants interacted with a 3D representation of a BPMN model using virtual reality devices (Google Cardboard and joystick) and were evaluated through structured comprehension tasks administered before and after the VR experience.

The results indicate that the immersive environment significantly improved participants' understanding of BPMN concepts. Notably, the visualization of token flow and the ability to navigate the model spatially contributed to deeper engagement, better abstraction, and improved process interpretation. Participants with limited modeling experience reported greater conceptual clarity, while more experienced professionals acknowledged the tool's potential for training and communication in real-world contexts.

The main contribution of this study lies in the empirical validation of a 3D VE designed specifically for BPMN education. Our findings support the integration of immersive environments into business process modeling curricula and professional development programs, particularly in scenarios where comprehension of process logic is critical.

Future research should explore longitudinal studies to assess knowledge retention over time and examine the effectiveness of immersive learning in collaborative settings. In addition, integrating 3D VEs with serious games, online platforms, and remote learning tools may further enhance their educational impact and scalability. While promising, the adoption of such technologies should be accompanied by usability evaluations and accessibility considerations to ensure inclusive learning experiences.

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Trustworthy Artificial Neural Networks Due to Process Mining in AI: Challenges and Opportunities

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Abstract. Although there has been a lot of progress in developing Process Mining (PM) algorithms and Artificial Intelligence (AI) techniques in recent years, no effort has been put in developing a common means of mining knowledge-based behavior of Artificial Neural Networks (ANN). In a design-science-oriented way, in this paper, elements of a new kind of AI-PM approach are outlined and demonstrated with ANN. These intend to enable (1) AI engineers to mine an ANN's inner processes to discover its knowledge-induced behavior, realize conformance checking, e.g. w.r.t. an ANN required behavior, and improve ANN due to enhancement. To illustrate the application of this new approach, a set of novel model views and algorithms are proposed, which are demonstrated on simple example logs. Findings show that AI-PM supports the clarification of ANN behavior: As the ANN's inner activities and knowledge generation can be mined, its non-transparent black box is unveiled and trustworthiness of ANN is supported.

Keywords: Artificial Intelligence · Artificial Neural Networks · Process Mining · Process Modeling · Artificial Knowledge Transfer · Knowledge Mining · AI-PM

1 Introduction

Recent breakthroughs in Artificial Intelligence (AI) research and in particular in research in deep Artificial Neural Networks (deep ANN) make it possible to carry out complex and non-linear data pattern analyses due to the AI's structure building learning procedures [1] and make it communicable in dialogues with Large Language Models (LLM) [2]. However, since the AI's knowledge is embedded in its inner structures, which are hard to understand, in particular ANN models are still seen as a non-transparent black box hard to be managed [3]: their behavior and performance cannot be unveiled, interpreted and explained. They so often lack in trustworthiness from human perspective. Contemporary attempts for increasing explainability and transparency in AI refer to feature visualization [4], sensitivity analyses [3], saliency [5] and knowledge extraction [6]. However, these approaches do not clarify the AI's behavior and x-rays on the AI's knowledge transfers.

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In business process context, Process Mining (PM) is well known as X-rays revealing what really goes on inside business processes [7]. It can be used to diagnose problems and suggest proper treatment based on process data. However, by now, PM has neither been used to clarify inner activities as knowledge flows or activations on ANN, nor to mine an ANN behavior based on its knowledge. Using AI in PM rather has focused on using AIs to predict next process steps [8]. But they have not been used for mining knowledge as resource object. The cruicial point is the following: Due to recent research to consider (artificial) knowledge to have a processual meaning of actual entities, which make AI-based systems to induce and evolve a behavior [6], the introduction of PM in AI context is prepared for knowledge-oriented behavior mining. The mission is that X-ray can reveal what is really going on in an AI's inner processes. What activations (such as entering a customer's chat into an AI-based chatbot, the LLM's answer generation for a dialog partner, a machine's instruction by deep ANN-based simulations and predictions, or an Enterprise Resource Planning (ERP) system that adapts its screens to the customer's current needs based on AI and ANN techniques) have in common is that all are recorded by information systems in live and real environments. Further, the systems observed leave trails in so-called action potentials or rather AI activations coming from simulated neuronal activity produced by neuronal compartments, individual neurons, groups of neurons, or the joint AI-based system [6] or the event-oriented process activities coming from workflow systems [7]. Bridging PM and AI therefore is attractive. If it was possible to mine the behavior of ANN from its activities, which refers in this case to its inner event data, and describe its behavior in a generally understandable language, such as a process modeling language, this kind of description supports the breaking into the ANN's well known dark black box. Further, if the complex behavior becomes understandable and interpretable due to this mined artifact, trustworthiness of ANN will be supported.

This article works out the prototype of a process mining in AI-based systems. It so suggests an approach to bridging PM and AI. On the one hand, it proposes the use of AI techniques in PM contexts. On the other hand, it proposes the application of PM techniques in ANN contexts. The main artifact proposed is referred to as AI-PM. It is demonstrated with ANN-specific examples and techniques. It claims to be a solution since the AI's complex pattern analysis capabilities can be used in traditional PM context and PM tools can be used to clarify the AI's inner processes. Thus, the research presented focuses on the following research question: *"How can behavior be minded from Artificial Neural Networks?"*

The research does not intend to provide an all-embracing, well tested and finalized mining tool for AI-PM. It rather intends to (1) introduce a new kind of tool, (2) clarify opportunities of AI-PM for AI-based systems as well as (3) clarify AI and knowledge mining techniques in PM context and (4) issue respective challenges. The practical relevance of AI-PM and related interesting scientific challenges make AI-PM a hot topic in AI management as well as AI-PM a hot topic in business process management.

The research approach is intended to be design-oriented in accordance with the Design-Science-Research Methodology (DSRM) [9]. Thus, the second section provides the foundation of PM, ANN and (artificial) knowledge transfers. The third sections presents the proposed AI-PM and its sub-components. Here, novel types of PM are presented, new modeling views to be mined are designed, and a workflow-based proceeding to realize AI-PM is clarified. The fourth section presents demonstration cases for AI-PM and presents and interprets the new kind of models mined. Finally, in a last section, results are discussed and the research is concluded.

2 Theoretical Foundation

2.1 Common Cases of ANN Training and Generalization

Since this research aims to consider ANN as object of investigation to be mined, the following clarifies AI-based application systems as a concept, ANN as technique as well as its foundational knowledge building mechanisms in form of training procedures.

Application Systems. In general, an *application system* terms a system that contains all programs that are developed, introduced and used as application software for a specific operational application example, including the technology, data and IT infrastructure, consisting of hardware, software, data, storage technology, communication and network, as well as the persons responsible for it [10, 11]. An application system can use an AI at a certain point of a process, which is referred to as *point-wise AI utilization* [6].

AI-Based Application Systems. An application system can be classified as an *AI-based application system* if that system supports the user's tasks with the help of hardware, software and/or logical elements (including organizational elements) to perform its tasks on the foundation of AI. Here, the application system considers AI as a foundation of an application house that builds on it. The AI represents the basis for on-building system components being triggered by the AI [6], because these have been attached onto the AI ground floor. For instance, when speaking about *ANN-based application systems*, here, numerous artificial neural structures and ANN represent the ground floor being wired. They map to processes because the ANN exhibit processual behavior [6]. By wiring several ANN structures, process networks can be induced. However, these ANN-based structures need to be trained to exhibit a useful behavior.

Training Procedure. By carrying out a training cycle, typically the data material is divided into two kinds of data sets [12]: About 80% of the data is randomly put into a *training data set*. This data is used to identify ANN weight changes, which is based on the training error E^T. The remaining 20% of the data is put into a *testing data set*. This data is used to determine the ANN's performance when working with unseen data. Its performance can be identified in comparing the ANN's output produced and the desired output, so that the test error or generalization error E^G can be identified. As training the ANN intends to optimize its performance under realistic circumstances, training aims to reduce E^G. If the training procedure was successful, the ANN embodies knowledge in numerous elements, such as its weighted structural connections: By being activated, it is able to exhibit or induce the trained processual behavior [6].

ANN Generalization. When realizing training procedures, care must be taken to ensure that correct *generalization pattern* is achieved. E.g. by choosing the correct training algorithms, its parameters, and ANN architectures. Common ANN cases of trained AI models are clarified in the following. The first case refers to a course of training or rather ANN model *overfitting* the data provided in the training and testing data sets. In the figure, one can see the ANN perfectly predicts the blue training data points but fails to predict the green testing data points. The model might be too complex - it simply encodes the data in the training set. One can say, the behavior beyond observed examples is not generalized correctly. The training data is simply learned by heart. Often, this is due to a training time too long, too many neurons, or too strict training parameters. The second case refers to an ANN model that *underfits* the data provided in the very same data sets. One can say, the model is too simple, e.g. because the training time was too short, the memory capacity of the ANN is too low because of too few neurons or too simple ANN architectures, or too loose training parameters. Here, too much behavior is allowed because the model overgeneralizes the observed behavior. The third and desirable case refers to an ANN model, that shows a *correct generalization*. One can say, the model represents the problem in a suitable way. It is not too simple and it is not too complex. This model is able to perform well on the entire data set, in particular the testing data set, not allowing undesired patterns, allowing desired patterns and not requiring to much model elements.

Critical Appraisal. Current error-based, competitive or Hebbian learning algorithms do not use PM techniques to (1) evaluate the AI's performance, which (a) go beyond standard training and testing procedures, and (b) go beyond the identification of overfitting, underfitting and correct generalization based on the analysis of error values. Further, PM techniques are not used to (2) describe the AI's behavior and (3) to compare the mined AI behavior with the a priori specified AI behavior, which can be interpreted as a kind of AI requirement. The research gap becomes clear here.

2.2 Common Cases of Knowledge Transfer and Generalization

As this research intends to mine knowledge of AI and with the aid of AI, as well as to realize a knowledge-oriented behavior mining, the following clarifies knowledge as concept as well as knowledge transfers and knowledge modeling languages as tools to clarify a system's behavior.

Knowledge and Tasks. Knowledge-intensive tasks can be characterized by a kind of physical or non-physical (digital) manipulation of resources [13], at which different knowledge transfers are being part [14]. Thus, by design, there is an interrelation of knowledge being transferred at a certain task realization and the behavior of a task participant, that comes up because of the knowledge presence, its occurrence and transfer at this task. This is why one can speak from knowledge to have a *processual meaning* [6].

Knowledge Transfers. Knowledge transfers are considered as the process of the identification of knowledge, its transmission from knowledge carrier to knowledge receiver and its application by the knowledge receiver [14]. Particularly, its application is essential, so that its effect or manifestation of knowledge transferred can be observed and gathered in a event log e.g. Please remark that knowledge bearer can be humans or AI-based process participants [6], which is essential for this research. However, knowledge transfers can be interpreted as *conversion* of different forms of knowledge being bound to at least one knowledge carrier [13]. While the first form of knowledge refers to well documentable *explicit knowledge* [15], that can be handed among process participants (human or AI) easily (e.g. a book), the second form of knowledge is hard to document as it is knowledge-bearer-bound (e.g. experience). It is referred to as *tacit knowledge* [15].

Modeling Knowledge Transfers. Having a focus on these two forms of knowledge, one can model the following four kinds of atomic conversions [15]: First, the *internalization* being modeled with an explicit knowledge form as input and a tacit knowledge form as output. An example refers to a person reading a book. It acquires knowledge from the book and integrates it into its mental knowledge base. Second, the *externalization* being modeled with a tacit knowledge form as input and an explicit knowledge form as output. An example refers to a person writing a book. Third, the *socialization* being modeled with two tacit knowledge forms as input and a tacit knowledge form as output. An example refers to two persons chatting about a book. Fourth, the *combination* being modeled with two explicit knowledge forms as input and an explicit knowledge form as output. An example is a person who reads information from a book and enters this information in a personal notebook.

Knowledge Instance and Generalization. Process modeling languages that enable the modeling of knowledge transfers refer to the semi-formalized KMDL [16] as well as the full-formalized NMDL [6]. Using them, the process of modeling refers to extracting common properties from a set of process instances, knowledge occurrences and observations from reality and creating a generalized process and knowledge model from them. The most granular and atomic modeling level refers to as an *actual entity* [6]. However, for simplicity, we often represent processual elements by abstract process step names. While the process model clarifies the system's behavior, the knowledge model clarifies the knowledge transfers. The models being constructed, here, intend to generalize over process and knowledge instances, so that they account for numerous situations.

Critical Appraisal. By now, knowledge transfers typically have been modeled by human modeling experts manually. To the best of our knowledge, there is only the Concept of Neuronal Modeling (CoNM) [6], that extracts knowledge objects on the basis of ANN activations and considers AI as model constructing experts. However, these knowledge objects extracted have not been used for mining a system's behavior based on event logs. Here the research gap becomes clear.

2.3 Common Cases of Process Mining and Generalization

As this research intends to transfer PM approaches to the AI domain, the following clarifies PM as concept, as tool as well as its foundational working mechanisms.

PM Definition. PM is a process management technique that enables business processes to be reconstructed and analyzed on the basis of digital traces in IT systems. As a metaphor, it enables organizations to X-ray their business processes, diagnose problems, and identify promising solutions for treatment. So, PM focuses on the identification of process knowledge that is embodied in the digital traces mentioned and documented in files called *event logs*. However, as PM does not only support the date-centered decision in companies, it is attractive for any event-oriented data generating domains.

Event Log. The event log is a structured file containing records and timings of hardware and software events and activities within a computer database. For instance, these can refer to the transactions from ERP systems, the progress of tickets in a ticket system or clinical treatment paths of patients in a hospital. Typical standard attributes per event include *case*, the *caseID*, the *activity*, its *timestamps* and further *(meta) attributes* [7].

Types of PM. In general, one can find three different types of PM, which differ in regard with (1) their input objects, (2) their output objects and (3) insights generated or knowledge extracted. The first type is labeled as process *discovery*. It refers to the process of reconstructing and extracting existing processes directly from event logs and event data without relying on pre-existing information or models. It produces a process model as an outcome. Thus, it clarifies the behavior on the basis of event log data. The second type is labeled as *conformance checking*. Here, existing process models are compared with event logs of the same process to identify deviations and matches between the two. Thus, it clarifies inconsistencies of processes observed in reality and the as-is processes as they have been planned, e.g. The third type is labeled as *enhancement*. This type of PM involves extending or improving an existing process model by using information about the actual process that has been recorded in an event log.

PM Algorithms. PM can be carried out by using various mining mechanisms, such as the *Alpha Miner*, the *Heuristic Miner*, the *Alpha++ Miner*, the *Duplicates Genetic Miner*, the *Genetic Miner* and the *Petrify Miner* [17]. Each algorithmic attempt has its individual strengths and weaknesses. If an AI is used at PM by now, attempts use ANN to generate sequence of events being interpreted as process steps [8] or generate an event log word-wise by the AI [18], which can be used in traditional PM context. However, none cares about (1) artificial knowledge flows, (2) mining knowledge as resource object and (3) using AI techniques.

PM Generalization. When PM with Event Logs, care must be taken to ensure that correct *generalization pattern* is achieved. E.g. by choosing the correct mining algorithm, its parameters and traces provided in the event log. Common PM cases of mined models are clarified in the following. The first case refers to a mined process model *overfitting* the traces provided in the event log. The model is too complex - it simply encodes the example traces in the event log. One can say, the behavior beyond observed examples is not generalized correctly. The second case refers to a mined process model that *underfits* the traces provided in the very same event log example. One can say, the model is too simple. Here, too much behavior is allowed because the model overgeneralizes the observed behavior. The third and desirable case refers to a minded process model, that shows a *correct generalization*. One can say, the model represents the problem in a suitable way. It is not too simple and it is not too complex. This model is able to reproduce the entire event log not allowing undesired traces and not requiring to much model elements.

Critical Appraisal. The current three types of PM do not use AI techniques. Further, the three types have not been transferred to AI domain. So neither AI activity data or (artificial) knowledge object data extracted has been used for the PM type of (1) discovery, (2) conformance checking and (3) enhancement, nor these types have been realized on an AI or ANN level (events refer to action potentials or AI activations). This is where the research gap becomes clear.

3 Design

In regard with the DSRM [9], the design presents research problem solution in form of artifacts, which will demonstrate their usefulness in the demonstration section. These artifacts refer to (a) the AI-PM conceptualization presenting new types of PM in AI context as well as AI in PM context, (b) the new modeling views considering knowledge-oriented PM, and (c) the AI-PM workflow issuing the methodological proceeding for realizing AI-PM. Each will be presented in an individual sub-section in the following.

3.1 Novel AI-PM Types

In analogy to van der Aalst's PM form definitions [7], the following presents the new definitions for the AI-PM to be designed.

AI-PM Model Discovery. The goal of *AI-PM Process Discovery* is to learn a processual, AI-based model based on an event log by using AI and PM techniques in order to mine a system's inner activities and clarify its behavior. For instance, the system might refer to a business process (as in traditional PM contexts) whose inner activities refer to tasks or knowledge transfers (being abstract representations of actual entity complexes) that can have all kinds of attributes, such as timestamps, transactional information, and resource usage. Here, AI techniques improve traditional PM by providing analyses on the basis of more complex data patterns. Further, for instance, the system might refer to an AI whose inner activities refer to activations or actual entities. As a common denominator for clarifying processual behavior of any kind of system, you can find the concept of actual entities [6]. Thus, the event log provides a collection of *actual entities* for cases or process instances observed. This is represented by a trace describing a sequence of actual entities. However, for simplicity, we often represent events or the actual entities by activity names only. AI-PM process-discovery techniques produce models following a certain modeling language, such as Petri Nets [19], Event-Process-Chain [20] or NMDL [6]. Thus, it uses pre-defined modeling elements, corresponds to a modeling language-specific syntax and applies modeling conventions. Therefore, mined models aim to be (1) easy interpretable for humans and (2) able to be parsed by machines (at least if full-formally specified). In particular the first point supports the *AI transparency increase*, because the AI behavior can become explainable - it is observable by the processual models mined and explainable by human interpretation.

AI-PM Conformance Checking. The goal of *AI-PM Conformance Checking* is to compare the mined behavior being represented by the processual, AI-based model and the observed behavior being embodied in the event log. Among the approaches to diagnosing and quantifying conformance, the search aims to find an optimal alignment between each trace in the log and the most similar behavior in the model. For instance, the system might refer to a business process (as in traditional PM contexts). Due to the AI-PM focus, additional AI models aim to produce better business process models than by traditional PM mined process models, because the AI is able to deal with more complex data patterns. So, they are ought to fit observed behavior better by design. The AI supports the ideal alignment of event log data (behavior observed) and the most similar model mined. In addition, it supports the ideal alignment of mined process models and processes planned. Further, for instance, as the system refers to an AI, the AI behavior mined can be compared with the AI behavior observed (embodied in the event log) or with the AI model specified prior its training (as a kind of AI behavior requirement). So, possible cases are (1) the model does not capture real behavior (the mined model is wrong), (2) reality deviates from the desired model (the event log is wrong), (3) the AI design and training leading to a certain event log are insufficient (the AI is wrong), or (4) the AI usage or its systematic and pedagogic testing comparable to school tests is insufficient (the AI application is wrong). Hence, the *AI assessment* incl. corrective interactions in regard with an *AI controlling* is supported, which enables the *AI monitoring* in live and offline contexts. Further, the *AI debugging* is enabled by comparing mined and desired models or rather AI behaviors.

AI-PM Model Enhancement. The goal of *AI-PM Model Enhancement* is to improve or extend an existing processual, AI-based model by using diagnostic information or knowledge extracted from the event log so that the model is more accurate, insightful or useful based on real observed behavior. After aligning, extending and improving the model and event log, the model can be replayed or rather rechecked with the event log (this can be interpreted as a repetitive AI-PM conformance checking). So, diagnostics should improve. However, any kind of model changes might lead to the adjustment of real-world system behavior. For instance, the system might refer to a business process (as in traditional PM contexts). If resource-related information is included in the event log or the model is enhanced with performance-related information, such as processing times, waiting times, or bottlenecks, the AI's information situation is improved, which might result in better AI models. As these better align with real-world processes, the mined models stand as basis for deriving implications on real-world system behavior. Further, for instance, as the system refers to an AI, the original AI model can be structurally enhanced, such as by adding or modifying elements in an ANN. After retraining and data gathering of new event logs generated by the new AI model, the remining of the new event log will show an updated AI behavior. As this new, mined AI behavior and the required AI behavior fits better, the AI has improved. This supports management of AI development and guided AI education by pedagogically valuable interventions [21].

3.2 New AI-PM Modeling Views

Aiming to clarify the AI's or an ANN's behavior on the basis of knowledge mined, the following presents the new modeling view designs of processual models that enable the new AI-PM forms presented in the previous Sect. 3.1. Since AI-PM operates on data being provided in event logs, the following assumes to have extracted knowledge objects [6] that have been collected in event logs. Possible origins of this kind of data is clarified in Sect. 3.3 when presenting the AI-PM workflow design.

Design of the HeuristicalKnowledgeView. The *HeuristicalKnowledgeView* intends to mine knowledge from *knowledgeObjects* and *informationObjects* provided in the entire event log by arranging them in an input-output relationship, so that (1) knowledge transfers are visualized, (2) conversions can be identified and (3) knowledge generation can be observed. By displaying the number of occurrences at all kinds of modeling elements mined, for instance the importance of knowledge routes can be clarified: The tool of a causal net is used to map out all the time-space history of different knowledge transfers. The model so visualizes how frequently different knowledge transfers take place. For example, the rarest knowledge traces can be excluded from the visualized model, while focusing on the most frequent knowledge transfers.

Design of the TokenizedKnowledgeView. Similar to the HeuristicalKnowledgeView, the *TokenizedKnowledgeView* clarifies the very same knowledge routes and uses the very same modeling elements. But instead of showing the number of individual occurrences at each modeling element, each arc provides places (visualized by circles) and transitions (visualized by rectangles) representing activities, which is inspired by PetriNets [19]. Thus, the model can be used to clarify the dynamic behavior as follows: The model provides tokens in order to clarify (1) the current state of a knowledge transfer system in context of a process monitoring, (2) the initial state of a simulation system that models the knowledge transfers mined, or (3) any dynamic behavior of the system during a simulation run at any point in a period of time. Since the very same transition rules of PetriNets can be applied to this view, the model clarifies possible knowledge traces by routes tokens can take: A first rule requires for activating a transition, its incoming places must provide tookens. Thus, conditions for initial knowledge objects can be clarified. A second rule requires the outcoming places must be equipped with tokens, when its preceding transition is activated. Thus, conditions for generated knowledge objects can be clarified. Further, as the PetriNet rule set applies, circles are not allowed to be connected directly. Instead, a transition needs to be in between circles. This, in addition, might lead to the visualization of unobservable knowledge transfers or rather transitions, which are indicated by black rectangles in this view. It is an interesting indicator for identifying unknown activities or rather knowledge trace relevant cases. However, this view is not clarifying conditions for individually occurring knowledge transfers, because it is not mining Boolean operators.

Design of the BehavioralKnowledgeView. As the previous two knowledge views are not clarifying conditions for individually occurring knowledge transfers, the *BehavioralKnowledgeView* focuses on the identification of Boolean operators. By providing the very same modeling elements, namely *knowledge objects*, *information objects*, *activities* and *conversions*, the Boolean operators of OR, XOR and AND are provided in addition. By this, the by knowledge induced behavior can be mined. For instance, this prepares the bottom-up, data-driven, automatic ProcessView generation on the basis of relevant knowledge objects extracted from ANN activations [6]. Examples can refer to customer intents or entities recognized.

Design of the ProcessView. Following the formal specification of the NMDL's ProcessView [6], the *ProcessView* to be mined is used to describe the behavior of AI-based or non-AI-based systems. Here, the focus is on the sequence of tasks or process steps and identifying the *control flow*, which is visualized by directed arcs. By using the Boolean operators of OR, XOR and AND in combination with these arcs, the system's behavior can be specified. As the control flow and Boolean operators are derived from the knowledge flows and Boolean operators mined from the BehavioralKnowledgeView, the AI behavior can be clarified on the basis of extracted knowledge mined (bottom-up modeling). Hence, based on the AI activation, the behavior of an AI system can be clarified, which includes its capability to act in a certain case of situation. From an AI knowledge management perspective [6], this is an essential step in order to assess the AI and to identify its AI competence. Further, as the AI's behavior can be made plausible on the data-driven basis of AI knowledge mined, a milestone for trustworthy ANN can be realized by design. The AI becomes auditable, because its behavior can be justified in a rigorous, data-driven way. However, instead of deriving Boolean operators from the BehavioralKnowledgeView, the ProcessView also can be mined on the basis of task events, only. Indeed, the comparison of top-down and bottom-up mining can lead to valuable insights, for instance if the ProcessView that has been derived on the basis of the BehavioralKnowledgeView and the ProcessView mined on the basis of tasks differ.

3.3 AI-PM Workflow Design

The three novel AI-PM types designed in the previous Sect. 3.1, can be realized by following the new workflow procedure presented in Fig. 1. Due to the size of the model presented here, the following clarifies its model compartments according to the yellow numbers, that can be found in this figure.

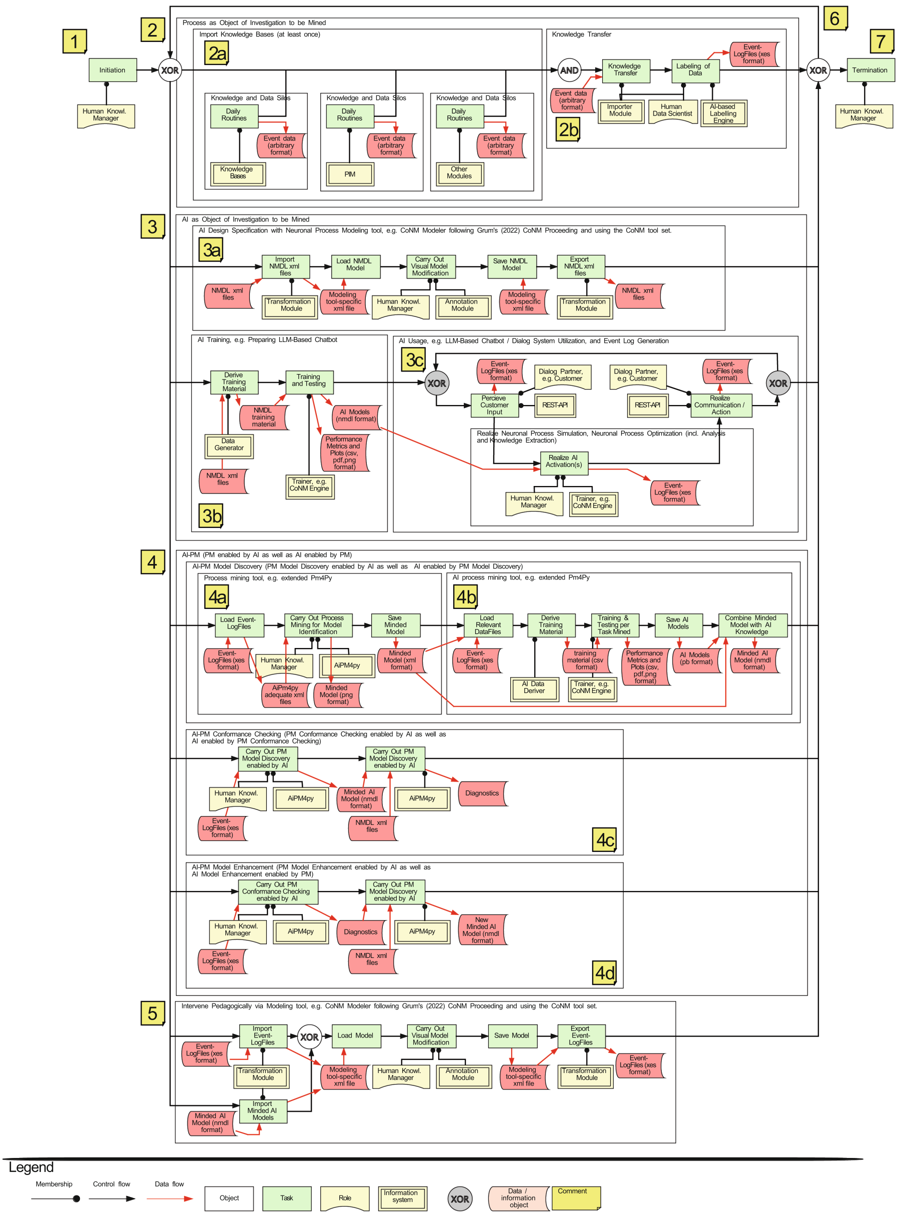


Fig. 1. The AI-PM workflow and various event log origins (as NMDL's *ProcessView*).

(1) The workflow is initiated by the human knowledge manager, that follows the role model of an AI-adequate knowledge management model showing human and AI in a symbiotic relationship [21].

(2) Traditionally, event logs are coming from various knowledge silos, such as from the Product Information Management (PIM) systems, Enterprise Resource Planning (ERP) systems, Customer Relationship Management (CRM) systems (cf. 2a). As this data typically does not have a PM-adequate data format, its knowledge will be transferred to the target format, which refers in the AI-PM case to the *xes file format* (cf. 2b). This kind of data stream can be used for PM enabled by AI. Here, for instance, events can be focused, that are caused by any kind of process participants, such as humans, AIs, machines and software.
(3) Focusing on the transfer of PM techniques to the AI domain, event logs can be generated by the AI(s) themselves, too. For instance, the AI is designed and constructed by using the modeling language called NMDL (cf. 3a). The full stack in form of a NMDL *xml file format* is used to derive the training and testing material from the NMDL's *SetViews*, so that an AI training and testing can be realized with the *CoNM engine* (cf. 3b). However, the repetitive ANN activation is realized on the basis of input data injected into the ANN, such as a customer request, which can be collected in the *event log file*. The corresponding ANN outputs (typically, these are displayed and used for chatting with the customer) as well as the ANN's inner activations coming from each individual neuron can be collected in the very same event log file. From particular interest for this contribution are the knowledge objects extracted from each neuron and integrated into the event log, because they have been proven to be relevant. The detailed extraction mechanisms incl. examples have been described by Grum [6]. The joint AI event log generation has been visualized in Fig. 1 at 3c.
(4) The three novel AI-PM types are modeled and explained in the following. At *AI-PM Model Discovery* (cf. 4a), in a first step, the tasks and knowledge objects are mined either from process data (cf. 2, coming from everyday systems) or from processual AI activation data (cf. 3, coming from AI utilization). As a result, the novel AI-PM modeling views are generated as they have been designed in Sect. 3.2. In a second step, for each knowledge-intensive task, the event log file is used to derive task-specific training material (cf. 4b). Thereafter, an AI training and testing is realized per task mined. Finally, the mined models and the AI models are combined.

At *AI-PM Conformance Checking* (cf. 4c), the *AI-PM Model Discovery* is realized. In addition, the initial AI specification (cf. 3a) is used for comparisons. As the initial AI model (using the full stack of the NMDL) and the mined AI models (using the AI-PM modeling views designed in Sect. 3.2) might differ, this kind of comparison can be used for *AI debugging*. For instance, this kind of conformance checking unveils, if the AI is indeed able to use its knowledge in a certain situation when facing the AI's behavior mined (based on event logs at 3c and mined in 4c) with the behavior originally planned (specified in 3a). Further, as the AI was utilized in everyday context in order to gather event data and to unveil AI incompetencies, the comparison of event log data, planned AI models and mined AI models can not only be used for AI assessment: On the one hand, the AI can be challenged in pedagogic tests in order to unveil AI incompetencies systematically. On the other hand, the comparison of event log data, planned AI models and mined AI models can clarify incomplete pedagogic AI tests. Thus, the valuable and pedagogic AI test design is supported. Going one step further, on the basis of these diagnostics and assessments, an *AI controlling* is supported, because a live monitoring is enabled indicating deviations of an AI from its behavior specified initially. In a kind of emergency cockpit, human knowledge managers are enabled to intervene if the monitoring indicates alarm situations. Further, the pedagogic valuable training of AI can be supported, because the AI's incompetencies are detectable: Having a detailed look on the models mined, ANN compartments can be identified, that are responsible for its competencies. Additionally, compartments can be identified, that are responsible for its incompetencies. Thus, an AI refinement training can focus on the effect reduction of compartments responsible for its incompetencies and the preservation or crystallization of compartments responsible for competencies [22].

At *AI-PM Model Enhancement* (cf. 4d), the *AI-PM Conformance Checking* is realized. In addition, the initial AI specification (cf. 3a) is not only used for comparisons. It is used for improving either the AI knowledge flows (manipulating the NMDL's *ActivityViews*) or the AI-induced behavior (manipulating the *ProcessViews*). For instance, the initial NMDL process models can be extended or improved through alignment between event log and model. Further, a non-fitting process model can be corrected through the diagnostics provided by the alignment. However, there might be cases, in which the *event log data* or the *mined models* are ought to be adjusted manually (cf. 5). This might require the manipulation of each event log entry. Further, there might be cases, in which the joint *AI model*, its *training* and *AI event log collection* are ought to be adjusted (cf. 3a, 3b and 3c). Of course, there might be cases, in which the joint real process system and corresponding workflows are ought to be adjusted (cf. 2a and 2b). Any kind of manipulations mentioned, go along with the re-mining and re-conformance checking.

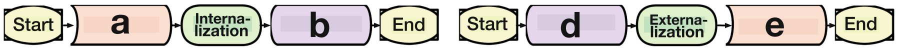
(6) As the workflow design asks for repetitive, creative and agile activities, the workflow designed allows the iterative proceeding. (7) The workflow is completed by the same human knowledge manager who started the process.

4 Demonstration

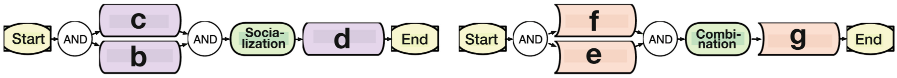
As the domains of PM and AI are brought together, AI does not only enable PM, PM also enables AI, which will be demonstrated in the following. The demonstration addresses the identification of the knowledge transfers designed on the ANN level [6] but using the AI-PM mechanisms to clarify an AI's behavior. So, by following the AI-PM workflow design (cf. Sect. 3.3), the AI designed has been used and extracted knowledge events have been logged (cf. highlighted 3c in Fig. 1). These have been used for carrying out the following AI-PM activities.

Mining on an Individual Neuron Level. Based on the event log created by the AI usage and each ANN activations, the isolated conversions can be mined from the individual neuronal levels, so that an *BehavioralKnowledgeView* is produced (see Fig. 2).

In Fig. 2a, one can see the activity of a single neuron, which is part of the deep ANN. Since this neuron is positioned at the very first input layer, the *information object a* is injected into the ANN right at the neuron considered. Obviously, this input and the neuron's activity is relevant, because the tacit *knowledge object b* has been extracted



(a) Internalization mined. (b) Externalization mined.



(c) Socialization mined. (d) Combination mined.

Fig. 2. The conversations mined from the event log.

by the CoNM's knowledge extraction mechanisms [6]. Hence, an internalization can be mined here on a neuronal level.

In Fig. 2b, one can see the activity of a single neuron, which is part of the deep ANN, too. Since this neuron is positioned at the very last output layer, the *information object e* is generated and provided by the ANN right at the neuron considered. Obviously, this output and the neuron's activity is relevant, because the explicit knowledge called *information object e* has been extracted by the CoNM's knowledge extraction mechanisms [6]. Hence, an externalization can be mined here on a neuronal level.

In Fig. 2c, one can see the activity of a single neuron being in dialog with two further neurons that provide the *knowledge object b* and *knowledge object c*. These further neurons can be on any position within or outside the deep ANN. It might also be, that one or two of these neurons refer to the very same neuron and these knowledge objects are extracted from previous time steps - via recurrent connection, the neuron is in a kind of dialog with itself. Future mining view extensions should mine the corresponding neuronal knowledge carrier in addition, so that this kind of information can be clarified based on the view mined. However, one can even interpret this as a kind of thinking process. With whatever neurons this neuron is in a dialog, the *knowledge object d* is generated and provided by the ANN right at the neuron considered. Obviously, this object and the neuron's activity is relevant, because the tacit knowledge called *knowledge object d* has been extracted by the CoNM's knowledge extraction mechanisms [6]. Hence, an socialization can be mined here on a neuronal level. Please remark the AND operator surrounding the two input knowledge objects. This is an indicator of a necessity of having both knowledge objects available to enable the current neuron to generate the *knowledge object d*.

In Fig. 2d, one can see the activity of a single neuron dealing with stored knowledge items, that e.g. have been produced by two further neurons and are labeled *information object e* and *information object f*. These further neurons can be on any position within or outside the deep ANN. It might also be, that one or two of these neurons refer to the very same neuron and these information objects are extracted from previous time steps - via recurrent connection or a memory cell. One can interpret this as a kind of remembering process. Future mining view extensions should mine the corresponding neuronal knowledge carrier timing in addition, so that this kind of timed information coming from previous time steps can be clarified based on the view mined. From whatever neuron(s) this neuron is in an interaction with, the *information object g* is generated and provided by the ANN right at the neuron considered. Obviously, this object and the neuron's activity is relevant, because the explicit knowledge called *information object g* has been extracted by the CoNM's knowledge extraction mechanisms [6]. Hence, a combination can be mined here on a neuronal level. Further, one can recognize the AND operator surrounding the two input objects. This is an indicator of a necessity of having both knowledge objects available to enable the current neuron to generate the *information object g*.

Mining Neuronal Knowledge Traces. Removing the limiting filter of isolating individual conversions of the previously presented mining focus on an individual neuron level, the mining of knowledge traces through the joint deep ANN is enabled. Thus, the following presents the mined models for the joint set of new AI-PM modeling views designed in Sect. 3.2. First, the *HeuristicalKnowledgeView* mined is presented, which can be seen in Fig. 3.

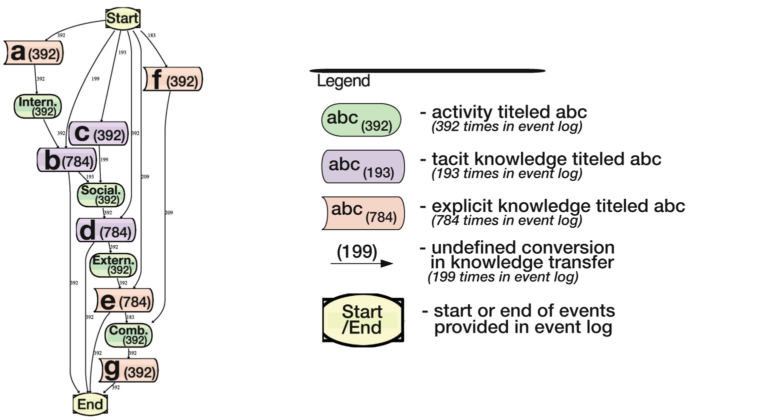


Fig. 3. Mining the heuristical knowledge view.

This model clarifies knowledge traces throughout all activities. Here, a certain sequential order becomes apparent. First, the *internalization* is realized, which comes from the injection of relevant information objects into the ANN. To be more concrete, the explicit knowledge labeled with *information object a* and *information object f* seem to be available at the very beginning of the ANN's usage. The *socialization* of neuronal groups follows. The occurring tacit knowledge called *knowledge object d* is unveiled, which has been extracted by the CoNM and stored as relevant knowledge in the event log. Further, the knowledge participation of the tacit knowledge objects called *knowledge object b* and *knowledge object c* is made transparent. Third, the conversion of *externalization* follows. Obviously, the group of neurons or rather the respective deep ANN's sub-compartment responsible generated the relevant *information object e*. Finally, the *combination* has been mined, which comes form the most advanced pattern recognition compartment produced at the very end of the deep ANN. It is used as the ANN's final output. It might refer to a chatbot answer or the classification result of an object recognized in a picture. Hence, this final output is stored as historic information being available for consecutive ANN activations. Next to each modeling element, a number indicates the respective total number of occurrences in the event log. Obviously, the *knowledge object b*, the *knowledge object d* and the *information object e* are very important, because these show the highest numbers.

Since this view does not allow the application of transition rules, the Fig. 3 does not clarify conditions of incoming and outcoming tookens. Further, it does not unveil unobservable transitions at all. So, the omni-presence of the modeling items is assumed. However, Fig. 4 shows the *TokenizedKnowledgeView* mined and cares about these issues.

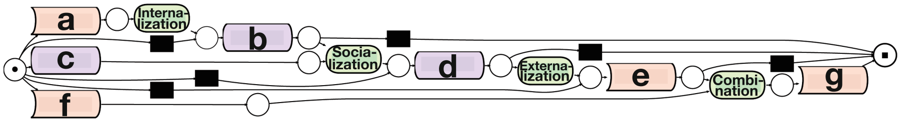


Fig. 4. Mining the tokenized knowledge view.

In the figure, one can identify unobservable transitions by the black rectangles. For instance, this unveils the necessity of having an activity for generating *knowledge object b*, which either can come from the case of an *internalization* or from the case of having a *socialization*. Further, the figure clarifies the conditions of activating a transition and so makes possible ANN knowledge routes transparent. For instance, the *externalization* requires the presence of the *knowledge object d*, which either can come from the route of (1) internalization-socialization-externalization, or the rout of (2) socialization-externalization or the route of (3) externalization-only.

Since this view does not mine Boolean operators, conditions of individual occurring knowledge transfers are not clarified by it. However, Fig. 5 shows the *BehavioralKnowledgeView* mined and cares about these kinds of issues.

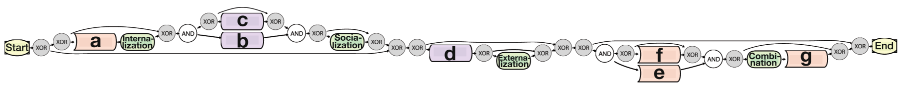


Fig. 5. Mining the behavioral knowledge view.

In the figure, one can identify all kinds of opening and closing Boolean operators. So, any case, any synchronization point and any parallelism can be identified by this model. For instance, the AND operators before and after the *knowledge object b* and *knowledge object c* clarify the necessity of having both knowledge objects available simultaneously in order to realize a socialization. However, the XOR operators surrounding the *knowledge object c* exclude this object from an omni-presence: It is an indicator for cases, such as the *internalization*, that only provide the *knowledge object b* but do not require the presence of *knowledge object c*.

Since this model has mined the full stack of Boolean operators on a knowledge view, by now, the model is not NMDL conform, yet: It is a mixture of the NMDL's *ActivityView* and *ProcesView*. It rather combines conversations being represented by arcs with Boolean operators, so that conversation cases as well as the by conversations and knowledge induced behavior becomes apparent. Although it does not clarify the control flow, it prepares the derivation of the control flow for the *ProcessView* to be derived. This view is fully formalized specified and is conform with the NMDL modeling standard. It is from particular interest, because of the following reasons: (1) The ProcessView so can be used to be processed by the CoNM engine. (2) The ProcessView so can be used to compare the observed AI behavior with the required AI behavior, because both are represented by the ProcessView. However, Fig. 6 shows the *ProcessView* derived from the BehavioralKnowledgeView presented before (cf. Fig. 5).

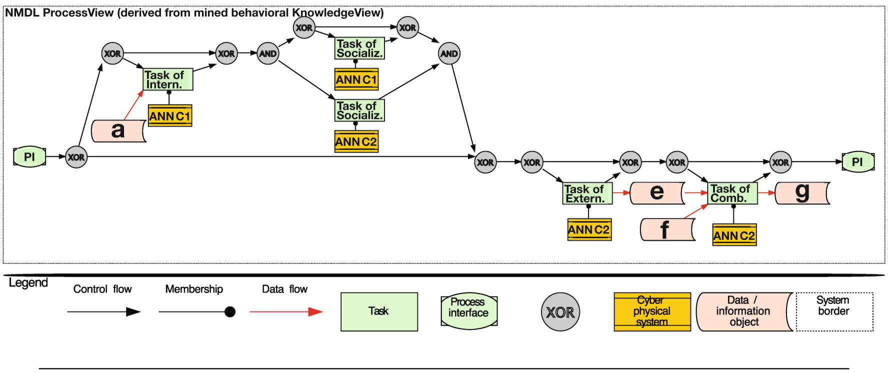


Fig. 6. The AI process mined.

In the figure, one can see the control flow (black directed arcs) connecting tasks and Boolean operators. Additionally, responsible process participants are attached to the respective tasks, Further, the mined data flow clarifies relevant human and machine interfaces. The process shown clarifies the AI's behavior, which is on the basis of knowledge extracted and mined from the event log. For instance, it clarifies what kind of neuronal group is responsible to deal with a certain input: the *Task of Internalization* is realized by the *ANN Compartment 1*. The input for this task, namely the *Data/information object a*, might refer to a certain part of a sentence or a part within an image. After having processed this input, the neuronal group called *ANN's Compartment 1* discusses its impression with the neuronal group called *ANN's Compartment 2* they both operate on their short term memory (*Task of Socialization*). For instance, their impression might refer to the remembering of a certain word in a dialog or to a certain picture as part of a film. The discussion output is externalized by the second dialogue partner *ANN's Compartment 2* - obviously, a relevant knowledge has been identified, so that it is stored in the long-term memory (*Task of Externalization*). The stored item is harmonized with further memories by *ANN's Compartment 2* (*Task of Combination*) before the AI's final output is generated. So, summing this up: *ANN's Compartment 1* has been very relevant for identifying a certain part of an image or sentence coming from the AI's current environment perception. Then, in having realized a knowledge transfer with *ANN's Compartment 2*, the second compartment obviously has been essential in order to come up with a certain decision because of its knowledge stored in the long-term memory.

5 Conclusion

The following concludes the research presented by summarizing and appraising it.

Summary. As part of a design-science-oriented research [9], this article has constructed an approach for AI-PM, which is designed to improves mining of traditional PM tasks by the usage of AI techniques on the one hand and enables knowledge-oriented behavior mining of AI-based systems on the other hand. The latter has been demonstrated by mining and interpreting the new model types of AI-PM in AI context.

Critical Appraisal. The research question (*"How can behavior be minded from Artificial Neural Networks?"*) can be answered with regard to the new AI-PM modeling views (cf. Sect. 3.2), namely (1) the *HeuristicalKnowledgeView*, (2) the *TokenizedKnowledgeView*, (3) the *BehaviroalKnowledgeView* and the (4) NMDL's *ProcessView*. These can be realized by following the workflow-based AI-PM procedure (cf. Sect. 3.3). As each modeling view puts focus on different mining aspects. In combination, they have functioned as valuable tool to mine *artificial knowledge* from an ANN's activities or rather event log data, which has clarified the ANN's behavior. Since individual modeling elements mined follow the NMDL's modeling elements, syntax and conventions, the models mined showed the AI's inner activities, visualized the knowledge generation, clarified knowledge transfers through the ANN, inferred the behavior induced by the processual meaning of the AI's knowledge and has lead to plausible interpretations. So, trustworthiness of ANN's can be supported due to PM in AI.

The new forms of AI-PM do not only support the AI behavior identification. As models mined follow well-known modeling standards, the models are interpretable by humans. So, by humans, the ethical AI behavior as well as the ethical AI use can be assessed based on *AI-PM Model discovery*. Due to the *AI-PM Conformance Checking*, deviations from an a priori specified and as ethically required AI behavior can be identified. The AI-PM so enables the identification of an unethical AI because of the deviations of an ethically required AI behavior. For this, the mined ProcessView on the AI and the ProcessView, that has been set up in AI specification phase (cf. Fig. 1 at yellow number 3a), can be compared. Further, *AI-PM Model Enhancement* supports the identification of model improvements. By this, for instance, standard AI training and testing procedures are complemented with the AI-PM tools. Another example is the identification of AI weaknesses or missing competencies, because the mined models indicate a missing but required behavior. A targeted AI model enhancement so can be implemented, which is part of an AI knowledge management [21]. Further, in context of pedagogic AI training, the creation of systematic AI competence tests is supported: If a desired behavior cannot be identified in mined AI models, the event log generation can be supported by modified event log generation procedures.

Outlook. Although first demonstrations have proven the technical functionality of AI-PM and these have demonstrated its usefulness, further examples need to be researched in order to increase external validity. This includes mining from AI-based systems using alternative AI techniques, too. Further, by now, the mining focus was set on knowledge objects. However, the NMDL provides further modeling elements, that should be included in current AI-PM mechanisms. If current modeling views designed are extended by additional modeling elements, such as the current knowledge carrier, the models mined can be interpreted more easily. For example, the dialog between two specific neurons or groups of neurons can be recognized immediately. Facing the title of this contribution, trustworthiness of ANNs is supported by AI-PM per design. However, this still requires empiric and experiments, in which users are faced with AI and AI-PM.

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Realizing the Full Potential of AI Applications Through Business Process Management

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Abstract. Many organizations have started leveraging AI applications to support isolated activities. However, in most cases this happens in pilot initiatives or small isolated usage scenarios, not through a systematic enterprise-wide roll-out. Business Process Management (BPM) can help to deploy AI-based solutions more systematically focusing on creating real business value. BPM helps to realize the full potential of AI by organizing the use of the AI-based applications to improve the performance of operational processes. It also leverages AI to improve the "process of process management, delivering higher quality results more efficiently. This article defines the role of BPM to deliver best value from AI. It outlines a business process-led approach to AI.

Keywords: Artificial Intelligence (AI) · Business Process Management · Digital Transformation · Value Realization

1 The Relation of Business Process Management and AI

The use of Artificial Intelligence (AI) applications, such as machine learning or deep learning, has become a key component of digital transformation initiatives [1]. An increasing number of organizations apply AI to improve performance in various areas. There are more and more examples of specific use cases [2–4]. However, to realize the full potential of AI, a systematic approach to its application and roll-out is required. Organizations require more than just a number of pilot initiatives randomly distributed across different company units [2]. They look for a controlled approach to realize the best benefits from AI. Business Process Management (BPM) can help to address this challenge. It focuses AI initiatives on high impact areas.

This paper defines AI and BPM as basis for the examination of the role of process management in delivering best value from AI technologies. The current status of AI usage is explained through selected case examples in Sects. 2 and 3. Those examples help to understand how the discipline of business process management can be applied to realize the full potential of AI. This is discussed in Sects. 4 and 5 and is a key contribution of this article. Based on those findings possible future research opportunities are identified.

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1.1 Definition of Artificial Intelligence (AI)

There is no universally accepted definition of Artificial Intelligence (AI) [5–7]. In general, it can be defined as an area of computer science that focuses on developing systems capable of performing tasks that typically require human intelligence [5]. Those tasks include, for example, the understanding of natural language, decision making or problem-solving capabilities. A similar common definition describes AI as systems demonstrating intelligent behavior by analyzing their environment and taking partly autonomous actions to achieve specific goals [7]. AI can be segmented into narrow AI, focusing on a specific task such as speech recognition and general AI with broader cognitive capabilities, across different domains [5]. This paper addresses both but focuses on general AI and specifically on its application in an enterprise context. It does not address the development of new AI software.

A key sub-domain of AI is machine learning (ML). ML focuses on developing and evaluating algorithms that extract patterns and functions from a dataset, hence, a number of examples. These algorithms, such as large language models (LLM), analyze a large dataset to identify underlying patterns in the data and relate input with output data. The outcome is a learned function that can then be used to convert input data into the appropriate output. The dataset could, for example, consist of the elements "annual income, "current debt" and "number of late credit payments". By examining a large number of such datasets, the algorithm can come up with a function that allows the prediction of a late payment based on the income and dept [8].

Deep learning is again a subdomain of ML where functions are represented as extensive neural networks. Each neuron of the network learns a simple function that is combined with others to deliver an overall complex function that can address more complex problems. AI with its key subdomains is shown in Fig. 1 [8]. Both sub-domains are relevant for this paper.

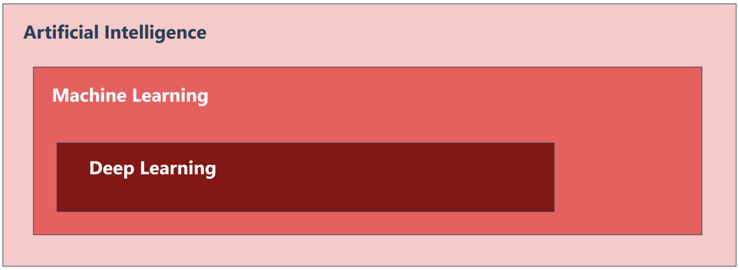

Fig. 1. Artificial Intelligence (AI) and its key subdomains [8]

AI has entered practice in "transformation waves" [9]. The first wave is referred to as Predictive AI. Here AI helps to forecast trends and with that make data-driven decisions. Generative AI was the second wave. It allows to generate content and have conversations with humans in real languages. Now we are entering the third wave of AI: Agentic AI. This AI system can autonomously execute tasks, make decisions within defined parameters and interact with other AI agents. Agentic AI can carry out entire business processes. It is not just about reacting to prompts or generate content. AI Agents carry out complex tasks and act based on internal and external data sources. Hence, they open a new dimension of automation where process instances are created ad-hoc based on a combination of events [10]. The waves of AI are illustrated in Fig. 2. All three waves of AI a relevant for this paper.

Fig. 2. "Transformation Waves" of Artificial Intelligence (AI) [9]

1.2 Definition of Business Process Management

Business Process Management (BPM) is the management discipline that moves strategy into people and technology-based execution, at pace with certainty [11, 12]. The discipline of BPM delivers the transparency over the operations of an organization required to take fast well-informed decisions and initiate related actions. This transparency enables the mitigation of trade-offs between conflicting goals, such as quality and efficiency, agility and compliance, external and internal alignment, innovation and conversation of good practices.

The BPM-Discipline manages the lifecycle of a business process, form strategy-based design, the implementation, execution and control of a processes. The control phase triggers the re-start of this lifecycle in case performance goals are not achieved. The definition of the BPM-Discipline (BPM-D) is visualized in Fig. 3.

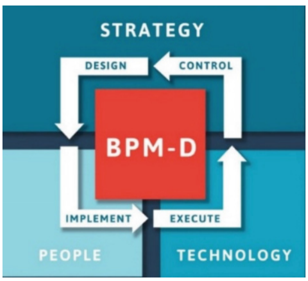

Fig. 3. Definition of the Business Process Management Discipline (BPM-D) [11]

The BPM-Discipline is realized, as any other management discipline, though appropriate processes: the "Process of Process Management" (PoPM) [13]. The PoPM manages the business process lifecycle. It helps to focus on what matters most, improve in an end-to-end context, using appropriate approaches, and to sustain achieved performance, hence, keep processes on track through ongoing improvement and launch new larger initiatives when required.

1.3 How Can Business Process Management Enable Value Through AI?

Digital transformation in general delivers its value through new or significantly enhanced business processes [14, 15]. It is not just about technology and data but the improvement of an organization's performance – executed through appropriate processes [16]. That's why enterprises who realize the full potential of digital technologies have a solid systematic process management capability in place. They apply a process-led approach to digital transformation. AI is one of those technologies, hence it also benefits from the capabilities of a BPM-Discipline. The role of business processes in digital transformation is explained in Fig. 4.

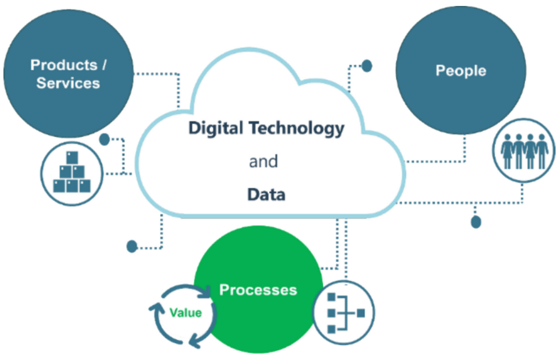

Fig. 4. Role of business processes for digital transformation [14]

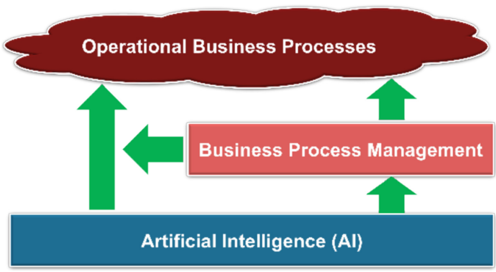

Fig. 5. Relation between Business Process Management (BPM) and Artificial Intelligence (AI)

However, AI is different to traditional digital technologies. It allows a degree of automation and information technology (IT) support never seen before. This leads to the questions, what role can the BPM-Discipline play specifically in the realization of the full business potential of AI? This topic is addressed in this paper and visualized in Fig.5.

2 Current Impact of AI on Business Performance

Many organizations have started using AI in a business context and achieve first performance improvements of their operational processes. There is also an increasing number of examples for using AI to manage the business process lifecycle. This section presents some of these AI application examples to illustrate the current impact of AI. It then discusses the challenge for realizing the full business potential of AI.

2.1 Direct Impact of AI on Operational Processes - Examples

Examples for the successful use of AI can be found across most business processes in many companies of different industries [2, 3, 17, 18]. To illustrate the variety of usage scenarios and stress the fact that AI supports all areas of an organization, the examples are segmented according to Scheer's Y model [19], grouping business processes into planning and execution related process, customer order or product related processes as well as overarching support processes.

In order-related planning processes different forms of predictive AI are for example used to provide sales forecasts and predict client behaviors, generate suggestions for inventory needs and resulting procurement requirements, even in executing simple procurement processes fully automatically, or predict supply chain bottlenecks to support the supply chain planning process. Examples for order-related execution processes are the prediction of production issues based on machine control data or the generation of maintenance instructions, hence a combination of predictive and generative AI.

Product-related planning processes leverage AI, for example, to validate characteristics of new product design, generate design alternatives, simulate possible machine behavior or generate code for the control of computer-controlled machines. The support of pick and pack operations through natural language controlled robots or the generation of pictures to detect reliably defects in quality control are examples for product-related execution processes supported through AI.

Examples for the use of AI in support processes are the generation of financial forecasts, prediction of hiring needs and pre-selection of candidates, the support of the development of marketing materials or the generation of code as part of IT processes.

The AI usage examples are summarized in Fig. 6.

While those examples refer primarily to manufacturing companies, there are also many AI usage cases in service industries. Examples are the support of decisions in the claims process in insurance companies, the simplification of the underwriting process by generating applicant profiles or the acceleration of a loan approval process in a bank by generating required information.

All those examples illustrate the impact AI already has on business operations of a company.

2.2 Indirect Impact of AI Through Enhanced Process Lifecycle Management

The examples for the use of AI to support process management itself, are structured leveraging the BPM lifecycle introduced earlier. Hence, usage scenarios of the process design, analysis, implementation, execution and control are identified. These examples are collected based on academic publications [20] as well as practice examples from process management tool vendors [21–24].

In the design phase generative AI can help identifying the goals of a specific process improvement initiatives by examining existing strategy documents. Based on those relevant value-drivers, areas for an improvement can be identified. Capturing process models from texts voice, images and other unstructured sources can replace or significantly shorten time consuming interviews. An initial version of the analysis of the captured processes can be generated through AI, leveraging the model information and common or best practice data. This simplifies and speeds up the identification of gaps and improvement opportunities. For the to-be design different alternatives can be generated, e.g. leveraging a database with appropriate reference models.

The implementation phase consists of people and technology-based realization activities. People change management documentation can be generated based on to-be process models and existing documentation, such as software-related electronic manuals. The IT-related implementation of a process can be supported through the generation of code or configuration settings of a software package as well as supporting user acceptance testing).

The degree of process automation can be significantly increased through the use of AI. Simple processes can be fully automated using a combination of AI agents to dynamically generate the process logic and execution of the resulting tasks through flexible, responsive workflows. People supporting a process can be enabled through the ad-hoc generation of training or other information simplifying their role in a business process.

In the controlling phase of the BPM lifecycle required improvement actions can be suggested or even executed based on process mining data. Monitoring dashboards can be automatically generated in the context of specific inquiries, users and goals. Users can ask for insights in natural language.

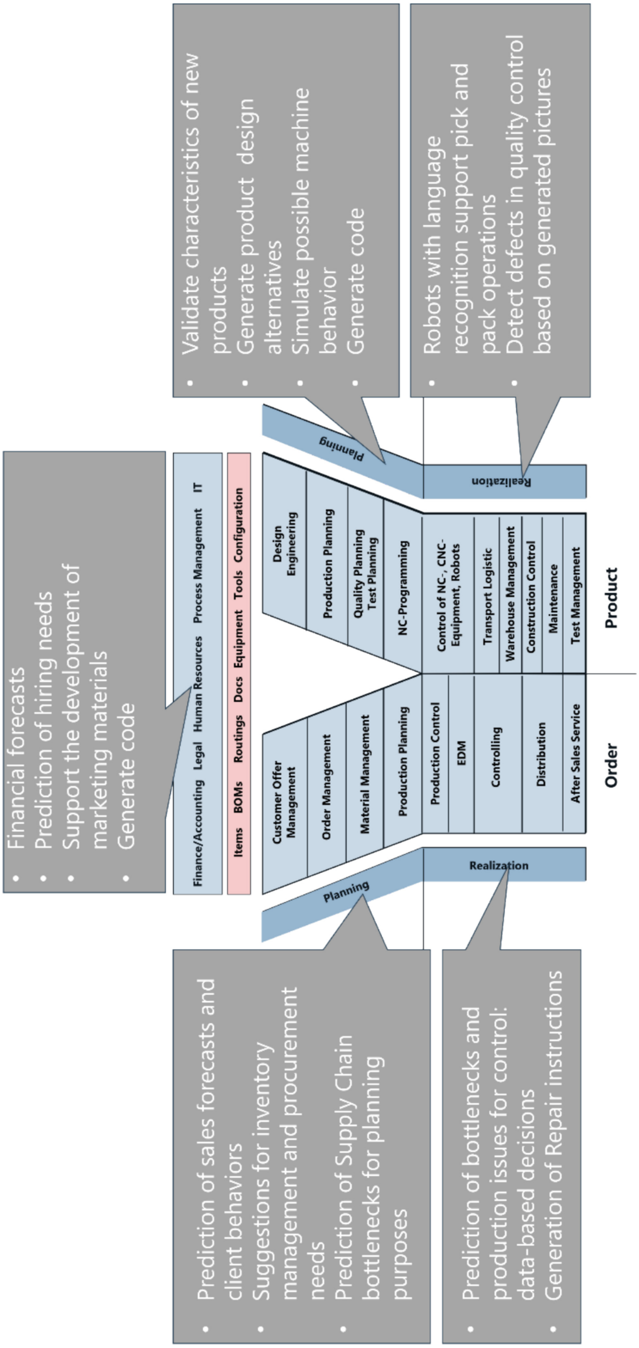

Fig. 6. Examples for the use of AI in operational processes segmented through Y-Model

Examples of the impact of AI on the process management lifecycle are summarized in Fig. 7.

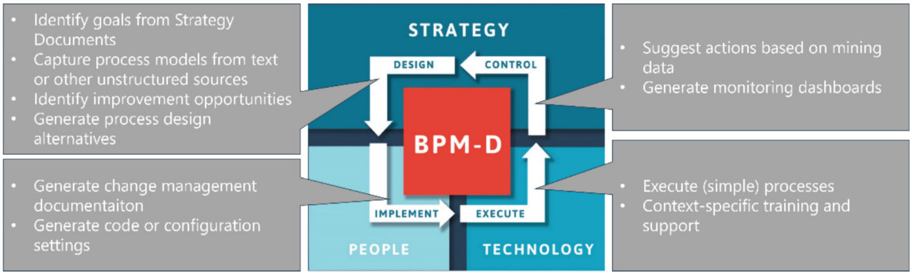

Fig. 7. Examples for the use of AI to support the process management lifecycle

Those examples illustrate how AI can improve efficiency and effectiveness of process management with that the value BPM creates for the organization.

2.3 Challenges to Realize the Full Potential of AI

The discussed examples for the use of AI show the potential and the impact it can have. Organizations have started to embrace AI. However, they face challenges on this journey to the AI-enabled organization.

There are a few key questions to be addressed [2, 3, 25, 37, 38]:

- How does an organization apply AI enterprise-wide to get best value out of it and not just use it to address a few individual tasks in AI pilot initiatives?
- What's a good way to transfer successful AI usage scenarios from other organizations?
- How do we best adopt AI-based solutions on an enterprise-wide level? How do we roll it out while mitigating involved risk and ensure ethical use of data appropriately?

An increasing number of organizations has a general strategy in place to adopt AI. They pilot the impact of AI in various tasks in a bottom-up approach. However, they lack a comprehensive approach to link their overall strategic AI-related intent to their business operations, hence, to transfer their AI strategy into execution. Where shall AI be used in which form and how can it be implemented to deliver best business value? What are the implementation priorities to deliver best impact?

A value-driven, fast and reliable roll-out of AI requires a systematic transfer of good and best practices from other organizations. Companies lack appropriate accelerators to achieve this. How can we avoid "re-inventing the wheel"? How do we benefit from existing lessons learned?

A more systematic use and roll-out of AI also requires an appropriate management and governance approach. How do we address the risks AI can bring, such as data privacy or copy right violations, biases or wrong results through "hallucinations"? Organizations start defining related roles but the overall governance model and how it is embedded in the organization is in many cases unclear.

Process management can help addressing those questions.

3 Value-Driven Adoption of AI in Operational Processes

The discipline of process management is about moving strategy into execution. Therefore, it can support the value-driven and systematic adoption of AI in operational processes of an organization. It provides the context to identify where to use AI and how to prioritize its roll out. BPM allows the systematic transfer of good practices through appropriate reference models, accelerating the roll out of AI. Process governance models with the related governance and management processes can be leveraged to address and mitigate the risks of AI implementations.

3.1 Provide the Context for the Systematic Use of AI in Operational Processes

Process management helps to provide the context for the comprehensive use of AI. A process delivers, by definition, a result of value [11]. Hence, using AI to improve the performance of an end-to-end process or to replace it by a better one realizes the business potential of AI. The transparency BPM delivers helps to decide where to use AI in which way and what controls are needed. It helps to ensure a process is consistent, so AI drives the desired outcomes. It enables the identification of data and governance requirements. With that, process management address key areas for a successful AI roll-out [39].

Process priorities defined, for example, through a process impact and maturity assessment, support the definition of appropriate priorities related to AI initiatives [26]. AI-related pilot initiatives can be lined up systematically to ensure they deliver best business impact by improving the end-to-end process.

A process-led approach to AI allows to increase the AI maturity systematically in a way that fits to the specific company environment [2]. The breadth of AI usage scenarios can be increased, the diversity of AI technologies employed grows. The value-driven roll-out of AI helps to increase leadership engagement and guides the use of data in decision making across the organization. The process context supports the development of the required AI resources, including data, people and technology. Process-led AI initiatives increase the number of real AI-based deployments as opposed to pilots to try out capabilities. The use of AI in an end-to-end process context also helps to establish the link to the overall operating model and strategy of the organization. It supports the incorporation of appropriate practices into processes to enable ethical use of AI.

The analysis of different views on a process, as described in the ARIS Architecture [27], helps to identify the opportunities for a use of AI systematically. It enables the identification of functions that can be supported or fully automated using AI. It guides the identification of related data needs and changes in the control flow of a process (if not generated through agentic AI). New or modified roles are determined and it is defined which of those can be taken over by AI agents leading to digital or hybrid workforce. And, very importantly, the analysis of the deliverables of a business process is used to examine if AI can create new or enhanced output. Typical questions an AI-related ARIS process analysis answers are shown in Fig. 8.

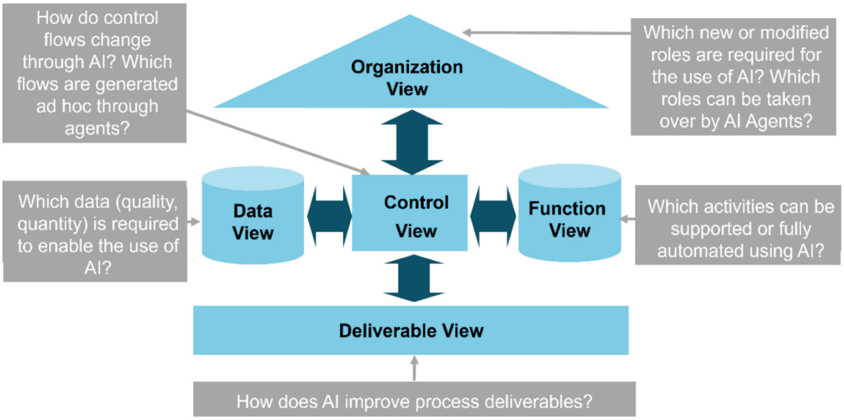

Fig. 8. AI-related questions an ARIS-based Process Analysis answers [25]

The identification of functions in a business process relevant for AI and the related data requirements [39] is a main aspect for a value-driven use of AI. A process described in a formal model, e.g. in BPMN format [28], shows all the "ARIS views", including functions and key data involved. Each function in the model can therefore be examined regarding the possible use of AI. Examples for typical criteria for the identification AI opportunities are the following:

- Use of natural language, pictures or other unstructured information
- Identification of anomalies in large datasets
- Prediction of results based on large complex datasets
- Generation of language based ad hoc reports based on large complex datasets
- Match of data elements or variant analysis in large data sets

While this process-led approach helps to use AI based on the requirements of the "traditional" process, it is important to examine also the AI-led design to achieve a potentially more transformational outcome of the initiative. Hence, it is about understanding the business opportunities AI can bring for a process. This means to address questions like:

- Can AI be used to achieve new or better deliverables of value from the process?
- Does AI allow structural changes, reduction of hierarchies or decentralization of sub-processes?
- Can AI simplify the process control flow, e.g. by taking over decisions through agentic AI?

Figure 9 illustrates the mutual influence of business processes and AI.

A machinery company had a major issue in their maintenance service processes. When service technicians determined that a part needed to be replaced, they determined in over 50% of the cases a wrong material number since many of the thousands of spare parts looked very similar. An analysis of this service process showed how AI can be used to address the issue. The creation of a database containing the pictures of all parts was created. Instead of guessing a material number the technician just takes a picture of the

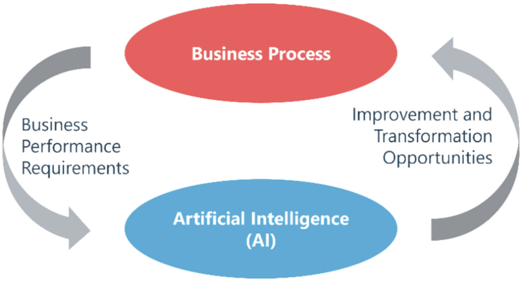

Fig. 9. Mutual influence of business process and AI.

part and AI selects the right number by comparing the picture to the data to determine the correct part number. Result is a correct number in over 90% of the cases. An excerpt of the AI-based service process is shown in Fig. 10. This also allows to simply the structure of the related service organization.

In a major commodity company, the financial month-end-closing is handled by 36 processes. In those processes the analysis showed that in 34 of those processes AI can have an impact. In five of those processes more than 10 functions have been identified as relevant for the use of AI. Examples for AI relevant activities are the matching of invoices in various unstructured formats with the related purchase order numbers, dynamic forecast of foreign exchange rates based on internal and external data, or the review and summarization of documents. This leads to a significant reduction of the month-end closing cycle time.

In a specialty pharmaceutical company, the examination of the early innovation processes regarding AI usage opportunities led to reduction of resources needs and cycle times. Process simulation showed that a traditional automation approach would lead to just over 20% cycle time reduction of key sub-processes whereas the systematic use of AI, especially for the generation of project specific reports, would lead to over 40% of efficiency gains.

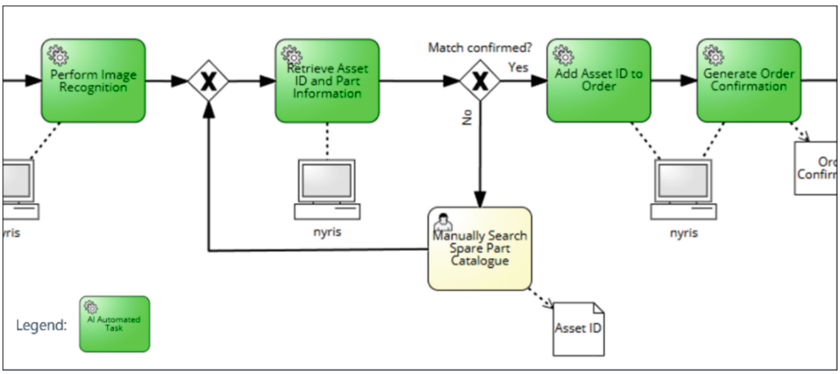

Fig. 10. Excerpt of an AI-based service process of a machinery company

The process context of the AI-based function forms the foundation for the selection and evaluation of the required AI assets, such as the appropriate Large Language Model (LLM) and the required data. Additionally, it provides guidance for the technical design of the interaction of different AI Agents to achieve the best possible degree of automation using agentic AI.

The simulation of different scenarios of the process models helps to predict the business impact the use of AI is expected to deliver. It supports the development and validation of related business cases.

3.2 Provide Governance and Management Processes for AI

Process management addresses different types of business processes [11]. Operational processes make sure things get done in the organization. Management processes focus on achieving best effectiveness and efficiency of operational processes. Governance processes provide the rules and guidelines for the management processes. Those governance processes are based on company goals, general trends, and internal or external regulations, such as legal compliance requirements. Since AI allows a higher degree of automation of operational processes, management and governance processes become increasingly more important. They operationalize the systematic application of AI-related risk policies which is crucial for a successful AI deployment.

If an operational process is highly automated using AI, for example through a combination of AI agents, it requires appropriate risk mitigation. Initially the results delivered by AI agents may have to be checked 100% to verify that results are logical and consistent and can be used by the next human or digital agent. After a certain period and possibly adjustments of the use of AI, the number of checks can be reduced. Management processes organize, for example, those checks. Governance processes describe the overarching guidelines in a systematic and actionable way. In the example, a governance process may define that initially a 100% check of results is required, after positive results over a number of weeks those quality controls can be reduced to 50% and another time span later to 10% or less. The use of AI is managed and governed appropriately. The roles of different business process types for AI are illustrated in Fig. 11.

In the context of AI, it is especially important to use governance processes to determine the right degree of freedom for the users to try out AI tools. In areas with high business risk, appropriate mitigation processes to avoid AI-related negative consequences need to be implemented. In lower risk fields people can get more freedom to try out new AI capabilities and with that move the adoption of AI forward.

The overall process governance and management organization helps to establish AI related governance and management in a company. Collaboration model, roles and responsibilities, available infrastructure and other assets can be re-used and, as necessary, expanded for AI. This establishes AI as a process improvement tool in the organization [11, 12, 29].

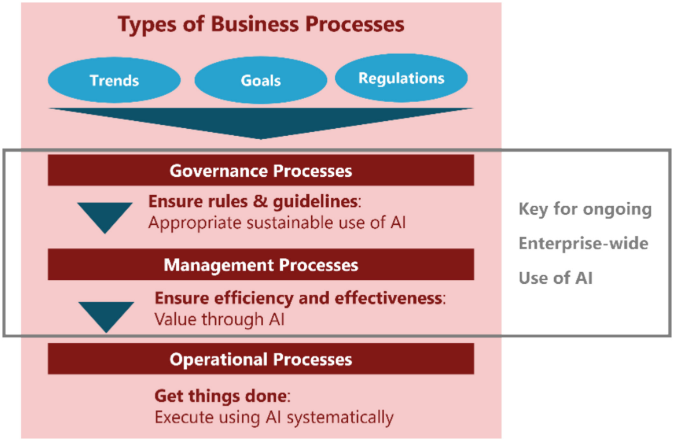

Fig. 11. Different business process types and their role for AI [11]

3.3 Transfer Good AI Practices Using Reference Models

The transfer of good practices within an organization or between organizations can be supported and accelerated through the use of reference models. Reference models are generic conceptual information models that formalize recommended practices for a special domain [11, 30]. Reference models allow an exchange of good practices in a structured way that simplifies and speeds up their implementation.

In the area of AI, reference models show how AI is used enabling a specific business process. Most important for AI is the combination of business process and data reference models that describe the information required for an effective use of the AI-based solution. The reference model should also include information about the required infrastructure, such as technology requirements or access to external data-sources. Such reference models could, for example, be provided by a software vendor that has already incorporated AI capabilities in an application, e.g. an ERP system [31].

The use of reference models provides a foundation for the definition of AI-based standards for an organization [32]. This simplifies the roll-out of good AI practices across

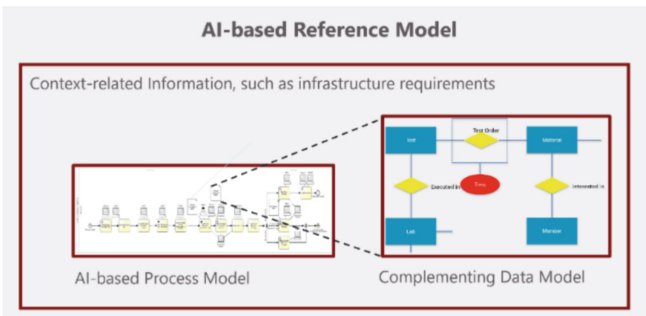

Fig. 12. Reference models for AI-based business processes

the company, such as different regional units or various product units. It supports the "assetization" of AI solutions [33].

The structure of reference models leveraged for the exchange and roll-out of AI-based business practices is visualized in Fig. 12.

4 Value-Driven Adaption of AI in Process Management

Adopting AI systematically for the BPM-Discipline means to use it in the context of a company-specific process of process management. Hence, it is not just about piloting it for individual tasks related to the process lifecycle management but as enabler of an end-to-end PoPM. The PoPM also needs to be expanded to support the systematic use of AI in a company. Both aspects are discussed in this chapter.

4.1 Improve the Process of Process Management Through AI

The process of process management defines how a specific organization manages the business process lifecycle [13]. It shows how process management is embedded into the organization. This allows to enable BPM through AI the same way, other operational processes are improved.

The company-specific PoPM is designed to deliver on the specific strategy of the organization and the related stakeholder expectations. Enhancing the performance of the PoPM improves the impact of AI on the operations of the company, contributes to realizing the full potential of AI for the organization. It provides the required guidance how and where to use AI capabilities of process management tools [21–24], such as modelling and mining, to provide best value to the organization.

The commodity company mentioned before had not formalized process management capability in place. They decided to start establishing a BPM-Discipline to create the transparency allowing them to improve their processes more systematically, especially to reduce cycle times. Therefore, an initial basic PoPM was defined. It consists of 9 sub-processes and 41 functions. 16 of those tasks have been identified for AI-based

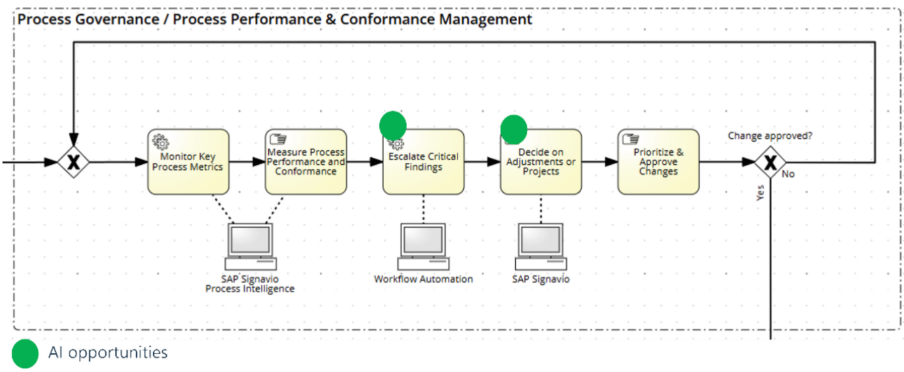

Fig. 13. Process of Process Management with identified AI usage opportunities - Excerpt

improvements. The use of AI, for example, to generate alerts and trigger actions based on process mining results is expected to deliver transformational improvements since it allows to govern key processes more effectively and drive ongoing improvements. An excerpt of the PoPM with identification of AI opportunities is shown in Fig. 13.

4.2 Expand Process Management Capabilities for AI

In order to fully support the effective use of AI, BPM capabilities need to be expanded appropriately. New or modified approaches, methods and related tools are added to the PoPM. The lifecycle of the process is managed more effectively [20]. As discussed, the adoption of AI in operational processes requires an enhanced analysis of processes, expansion of governance models and development of AI-based reference models.

Automation through agentic AI requires new enhanced modelling approaches. AI agents execute tasks independently, take decisions and interact with other agents or with humans. As a consequence, detailed process instances are not defined upfront as process types, but generated in "run time" based on context information and the interaction of the various agents [10, 34]. Hence, an appropriate modelling approach is required to describe those process automation mechanisms. This expands the purely business-oriented process models through a combination of business and technology-related information.

Existing methods, like BPMN, can be extended to define agent-based processes, e.g. by using lanes to show an agent's role in the automated process. In case of a hybrid workforce, there are lanes representing humans and others representing agents [35]. This shows how agents impact the control flow of process instances. The underlying automation platforms require descriptions methods addressing the agent-specific behavior by specifying, for example, the LLM used, relevant interface (API) tools or the memory leveraged. The platforms are configured through those models [10, 36]. The definition of AI agent-based automation is illustrated in Fig. 14 [16]. It includes relevant technical information, like the used AI model, data storage and interface (API) tools.

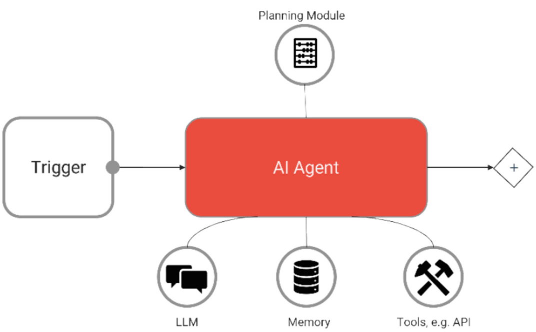

Fig. 14. Information model for process automation with Agentic AI – example/excerpt

5 The Way Forward of Process-Led AI

This paper shows how process management is used as the discipline to drive best value from AI through a systematic enterprise-wide adoption of different AI applications. It also shows how AI can enhance the BPM-Discipline itself, making a specific process of process management more efficient and effective. However, the journey of realizing the full potential of AI through process management has only started. There are still many important research and development opportunities for process-led AI, such as:

- Definition of process-centric usage scenarios in form of extended reference models: What do leading AI practices for a specific business process look like? What are the data and technical requirements? How do we package this information in easy-to-use reference models?
- Extension of process governance: How do the governance processes have to change for AI? How do we leverage process management tools, such as modelling and mining tools, to include AI-related governance?
- AI-enabled process management: How does the ideal process of process management leverage AI? How are BPM tools, further enhanced through AI? What is the best way to model agentic AI to support a business process?

Process management has become key enabler of value through enterprise-wide use of AI. And the journey has just started.

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A Generative and Restrictive AI Interplay in Entity Matching and Retrieval

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Abstract. Although the recent emergence of Large Language Models (LLM) has introduced new approaches to Entity Matching (EM), there has been limited effort towards combining diverse AI techniques and developing corresponding implementation frameworks. In a design-science-oriented way, this paper introduces a new kind of interplay between generative and restrictive AI for EM. This interplay is operationalized through the development of a novel orchestration framework and empirically demonstrated through the integration of three distinct AI types: (1) a fuzzy, restrictive Deep Learning-(DL)-based AI, (2) a fuzzy, restrictive Machine Learning-(ML)-based AI, and (3) a generative LLM-based Retrieval Augmented Generation (LLM-RAG). This real-world implementation demonstrated the efficacy of the framework. Findings show that the combination of (a) the modular software architecture having module layers, system layers, and usage layers and (b) the master-slave infrastructure model are suitable for the framework construction and enable enterprises to deploy containerized AI-modules independently or in orchestrated workflows. Each AI-module operates in isolated Docker containers, ensuring portability and scalability in heterogeneous and distributes hardware infrastructures. Furthermore, the AI interplay supports the combination of advantages of different AI techniques. Contributions include a reusable architecture for AI orchestration in further domains.

Keywords: Artificial intelligence · AI orchestration · vector databases · entity matching and retrieval · LLM-RAG · Deep Learning · Machine Learning · Random Forest

1 Introduction

Artificial Intelligence (AI) is undergoing transformative growth, marked by the rapid emergence of Large Language Models (LLMs) that redefine technological capabilities [1]. While open-source innovations have enabled better access to these tools, a critical disparity persists: enterprises often lack the infrastructure, knowledge, and financial resources to harness AI effectively [2], unlike their larger counterparts. Consequently, enterprises miss out on valuable automation opportunities for algorithms, tasks and processes that can be easily automated. To date, different AI techniques have been implemented and realized on specific hardware, but no effort has been put into realizing an

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individual AI and managing cooperative AIs being realized in decentralized and heterogeneous hardware infrastructures.

If it was possible to acquire AI realization(s) easily in an infrastructure-independent way, and control the deployment of current AI model versions, even most complex AI-based tasks can be automated. This paper proposes a modular orchestration framework that empowers enterprises to deploy AI-driven solutions for complex tasks, such as data matching and retrieval. Here, existing software and infrastructure architectures are being combined and adapted for utilizing modular and independent AI applications. Thus, the research presented focuses on the following research question: "*How can the complex task of data matching be supported by interplaying modular AI systems?*"

The research does not intend to provide an all-encompassing, well-tested, and finalized framework for interplaying AIs or a fine-tuned AI system complex for matching and retrieval tasks. Rather, it intends to (1) demonstrate the framework for clarifying how to implement an AI matching and retrieval system complex. It intends to (2) conceptualize orchestrated AI system modules, that consists of two restrictive, fuzzy matching AIs and one generative LLM-RAG (Large Language Model - Retrieval Augmented Generation) - all using different AI techniques: The restrictive, fuzzy matching AIs are using Deep Learning (DL) and Machine Learning (ML), and the generative retrieval AI is using LLM-RAG. Further, it (3) intends to progress current matching and retrieval approaches by interplaying AIs: Restrictive matching techniques classify data pairs by determining whether they constitute a match. Incorrectly identified matches are then forwarded to the generative LLM-RAG, which retrieves additional potential data entries for matching, which are then re-processed by the restrictive AIs.

As this research is designed as design science outlined by Peffers et al. [3], the remainder of the article is structured as follows. The theoretical foundation of this article refers to the foundation of matching as well as AI design and workflow context, which is addressed in the second section. In the third section, we first present the design of the interplay of one generative and two restrictive AIs. Then the corresponding framework for technically realizing interplaying AI-based systems is designed that facilitates the independent and modular implementation of an AI orchestration system for various AIs. In this research, it is exemplified with two restrictive, fuzzy matching AIs and one generative LLM-RAG-based AI. The fourth section demonstrates the AIs and respective framework in a real-world business context. Thus, in the fifth section, the joint research artifact is evaluated with regard to requirements on its design. The final section concludes this research with a discussion of the findings.

2 Theoretical Foundation

2.1 Matching and Retrieval

Entity Matching. Record linkage [4] or deduplication [5], also known as *Entity Resolution* (ER) aims to identify and canonicalize records that refer to the same real-world entity. Here, *Entity Matching* (EM) refers to a critical step in ER that uses techniques to identify matching records from potential matches filtered by the blocking step [6].

Faced with the recent emergence of LLMs and new zero- or few-shot paradigms to EM [7–11], Wang et al. differentiate three strategies for LLM-based EM: (a) matching, which identifies the record to be the same as an anchor record or not, (b) comparing, which identifies the record out of two that is more likely to match the anchor record, and (c) selecting, which directly chooses the record from a list that is most likely to match the anchor record [12].

Information Retrieval. The subject area that deals with computer-aided searches for complex content and falls within the field of information science, computer science and computational linguistics is known as *Information Retrieval* (IR) [13].

Usually, it is used in the context of database or information system queries and describes the process of being able to provide specific information from a large amount of unsorted data. IR is therefore about finding existing information again. However, due to the emergence of LLMs, attempts to augment LLMs with external storage have come up that can be used to retrieve information from this external storage by using LLMs [14]. So, for instance, a list of potential matches for each entity record can be retrieved. Furthermore, continuously extending the augmented LLMs with all potential matches at a time allows LLMs to generate better retrieval suggestions.

Critical Appraisal. Contemporary matching and retrieval attempts have considered several AI techniques, such as DL, ML and LLMs [12]. However, they have not considered interactive AIs to realize matching and retrieval tasks, yet. This highlights a clear research gap that this work aims to address.

2.2 AI Design

Generative AI. The generative AI is a metaphor of an area of AI that focuses on generating new content, such as text generation, image creation, music production or video generation. In contrast to traditional AIs, which in particular analyze existing data, generative AI generates original and creative outputs. Prominent examples refer to general purpose LLMs (e.g. OpenAI's *GPT-3* [15], Google's *Bard* [16], Meta's *LLaMA* [17], DeepSeek's LLM [18]), as well as dozens of task-specific LLMs for coding, scientific knowledge, dialog, finance, e.g. [14].

In particular, the *Retrieval Augmented LLMs* (LLM-RAG) are attractive for matching and retrieval tasks of this research, since standard LLMs may have limited memory and outdated information leading to inaccurate responses. By integrating external, up-to-date storage, LLMs are able to retrieve relevant information to accurately answer with references and utilize more information [14].

Restrictive AI. As an antonym of *generative* AI, we propose restrictive AIs to focus on the filtering of content shown. For instance, this refers to a classification task, where targeted classes refer to either be part of a class or not. This task, for instance, can be implemented by using DL-based or ML-Based AIs. In the matching context, classes for instance can refer to *is-a-match* and *is-not-a-match*. Of course, multiple classes or rather match dimensions can also be considered. However, when processing numerous objects, each object can be assessed to be a match. The objects that are not part of a matching class can be sorted out or rather filtered.

AI Orchestration. Following the metaphor of an orchestra, for realizing AI-based tasks, numerous components need to be dynamically activated or rather orchestrated. Here, one can identify (1) an *entity to coordinate* AI task requests [19], (2) *AI models* that can be considered as interchangeable knowledge bases [20] being distributed and transferred among different computing levels [21], (3) transmissions of *service requests* for an AI and (4) corresponding *AI results* [20], (5) *file transfers*, such as training, testing and activation data [20], as well as (6) programming library-specific *source code* [22].

As these components and AI tasks can be processed at different computing units [23], the computing-node independent component transfer is attractive to realize an AI. Here, in particular, an MQTT-based communication and Docker-based containerization have been proven to be efficient [22], since these can provide AI expertise flexibly at diverse computing levels: Similar to a conductor in an orchestra, relevant components can be requested via MQTT's message channels. Then, specialized knowledge bases as well as data and file contexts are deployed so that artificial knowledge transfers can be realized efficiently. Here, Docker enables the separation of AI applications, AI models and data from the underlying hardware infrastructure, so that these artifacts can be delivered individually. We refer to this as *modularization of AI*. Further, the AI-based application can be managed in the same way as the infrastructure can be managed. For instance, at run time, (a) the current AI model can be exchanged, (b) the AI's processing can be swapped from CPU to GPU, (c) the processing node can be altered or (d) the AI load can be transferred among several AI instances. By taking advantage of Docker's methodologies for shipping, testing, and deploying code, the delay between writing code, training an AI, distributing it and running it in production is so reduced by design [24]. However, in addition to orchestrating AI task components, numerous AIs can be orchestrated to take care about more complex tasks [22,25]. However, the concept of *orchestrated AIs* has been realized in numerous experiments, such as [22,25], and corresponding mechanisms can be found in the public AI-CPS repository [24] under Open-Source license.

Critical Appraisal. To date, the flexible AI realization has been demonstrated in Industry 4.0 settings and numerous classification tasks. However, the AI orchestration has not been used for demonstrating the interplay of generative and restrictive AIs, yet. Here, the research gap becomes clear.

2.3 Process Modeling and Workflow Design

Process Modeling. Principally, process modeling (PM) is the analytical representation of an organization's workflows or business processes. For this, typically, diagrams or models are used to visualize and improve how tasks, information, and decisions flow [26]. For instance, this helps to identify inefficiencies, standardize operations, and support process optimization or automation. Hence, PM is attractive to design the interaction of different AIs and human process participants.

By now, numerous process modeling languages have evolved, such as *Petri Nets* [27], the *Event Process Chain* (EPK) [28], the *Business Process Modeling Notation* (BPMN) [29], or the *Knowledge Modeling and Description Language* (KMDL) [30]. Because of the intention to describe, manage and control the AI interplay on the one hand and to anchor it in business contexts on the other hand, the PM has been based on the *Neuronal Modeling and Description Language* (NMDL) [31]. The NMDL has proven to be the superior modeling language for contemporary AI-based systems [32]. Thus, the orchestration design to be offered by the implemented framework will be derived from the NMDL models prepared automatically.

Workflow Systems. While PM primary intend to manage, model, analyze, and optimize full processes, workflow systems refer to software platforms that define, manage, and automate business processes by coordinating tasks, data, and users according to predefined rules [33]. They so help to ensure that work is completed efficiently, consistently, and in the correct sequence across an organization. Prominent workflow system examples refer to (1) *Signavio* [34] or *ARIS* [28] being PM tools providing selected workflow features, (2) workflow systems (with limited PM features), such as the low-code platforms *Microsoft Power Automate* or *Zapier* [35], and (3) PM tools with integrated workflow systems, such as *Camunda* [36], *Bizagi* or *ProcessMaker* [37]. However, as only the Concept of Neuronal Modeling (CoNM) tool has demonstrated process-triggering and worklow-triggering AIs [32], the orchestration design to be offered by the implemented framework will be derived from its mechanisms. So, for instance, AIs can be triggered by routines, by knowledge generated by an AI, or by interplaying AIs and human process participants being integrated via workflows directly with the corresponding AIs.

Critical Appraisal. Up to now, the NMDL's *ProcessView* has not been used for deriving the technical infrastructure (for driving the AI realization) automatically, yet. Further, as the NMDL and its CoNM tool have not been modularized and containerized for driving the technical infrastructure, its realization in distributed, heterogeneous hardware infrastructures has not been demonstrated, yet. This is where the research gap becomes clear.

3 Design and Development

To enable the interaction of multiple AIs and their technical realization, various components are designed, each offering a unique perspective on the overall design artifact. According to the design, components have been developed and implemented, so that they are ready to be demonstrated. Thus, this section puts a focus on the following three design perspectives.

First, from a user perspective, the cooperation of (1) generative AIs, (2) restrictive AIs and (3) humans is conceptualized in Sect. 3.1. Second, on the software side, the architecture is organized into three hierarchical abstraction layers, clarifying the flow of data and functionalities within the system (cf. Sect. 3.2). Third, from a hardware perspective, infrastructural architecture represents the physical deployment and execution of the system (cf. Sect. 3.3).

All together, these design components aim to maximize modularity and reusability throughout the system, while minimizing individual complexity. Furthermore, maintainability and scalability are advocated due to the modular design. However, the requirements provided in Table 1 have guided the research and development. Further, they suite as quality gates for onbuilding research.

3.1 Generative and Restrictive AI Cooperation

The interplay of generative and restrictive AIs is designed in the following. Please remark, although speaking from one *ML-based AI*, one *DL-based AI* and one *LLM-RAG-based AI*, Fig. 1 only presents three concrete types of AIs. However, an arbitrary number of AIs and different AI techniques can be used to concretize the schematic cooperation of generative and restrictive AIs.

Table 1. Requirement collection.

ID	Requirement Description
1.	**Req.** *(Modularity)*: The framework need to ensure modularity, so that AI modules, such as different AI systems, and each AI system's components, such as its training data, AI model, programming library or database, can be deployed and replaced without affecting the overall system functionality in running status
2.	**Req.** *(Scalability)*: The framework need to ensure scalability, so that several AI instances from the same AI module can be started im parallel. So, each instance can process AI requests individually and workload can be balanced
3.	**Req.** *(Speedability)*: The framework need to ensure speedability, so that it can handle large datasets. This refers to techniques to increase retrieval speed, such as GPU acceleration, vectorization and storage techniques. Further, as data can grow, this demands for expanding the database or switching to alternative database types in operation mode
4.	**Req.** *(Usability)*: The framework need to ensure usability, so that both technical and non-technical users are enabled to interact with the AIs. While the first might refer to AI and IT experts that are responsible for realizing continuous training procedures or designing the AI workflow, the latter might refer to knowledge workers being responsible for using the AIs in their individual process context. For instance, a visual process modeling language will be valuable for both: technical users are enabled to design the AI interplay and non-technical users are enabled by state monitoring of the current AI interaction
5.	**Req.** *(Updatability)*: The framework need to ensure updatability, so that individual AIs (managed as AI module) or its building blocks (managed as components) can be separated to be constructed, tested, deployed and brought to operation mode. So, for instance, the extension of training data can be separated for realizing an AI training

In the figure, one can see the *start* of the matching and retrieval task on the very left and its *end* on the very right. While the *data flow* is visualized with red arcs, this clarifies input and output data objects of a certain task (visualized in green), black arcs clarify the *control flow* or rather sequence of tasks and process behavior.

The process starts with an *initial matching request*, that is processed by both restrictive AIs, namely the *ML-based AI* and the *DL-based AI*. While the DL-based AI (e.g. ANN) shows strengths in contexts of large data sets, the ML-based AI (e.g. Random Forest) shows strength in low data set contexts. If its matching is successful, the control flow path of *no problem case* is followed. Faced with a rate, an *optional check* is realized by human experts. This rate can be reduced if the AI complex is trusted well. However, any valuable, human work complements the *training data*.

If no math has been verified by one of the restrictive AIs, the generative AI is requested to produce a predefined number of *AI match suggestions*. The more *data bases* are connected to the *LLM-RAG*-based AI, the better the suggestions are. As any AI suggestion is verified by the restrictive AIs again, a kind of generative and restrictive AI ping-pong can be realized, which is visualized by the closed feedback loop.

In the case, the AI interplay has not been successful, for instance, if a certain number of loops has not lead to an satisfying match performance criteria, the *manual investigation* is realized by a *human* process participant. As a kind of second-level support, the valuable match identification is determined by intensive human labor. Results are taken to complement the *training data*. Thus, in the long run, the refined AI models will capture former problem cases in a AI-CBR manner [20].

3.2 Software Architecture

From the bottom up, there are three layers: the module layer, system layer and a usage layer, each corresponding to a different user and task (see Fig. 2). This architecture follows a layered architecture, where each layer can exclusively communicate with neighboring layers [38]. This further enhances the modularity and reusability of each component, making it easier to identify the role and functionality of each layer. However, it also introduces additional complexity and overhead when considering the system as a whole. To address this issue, it is advisable to minimize unnecessary traversals between layers as much as possible.

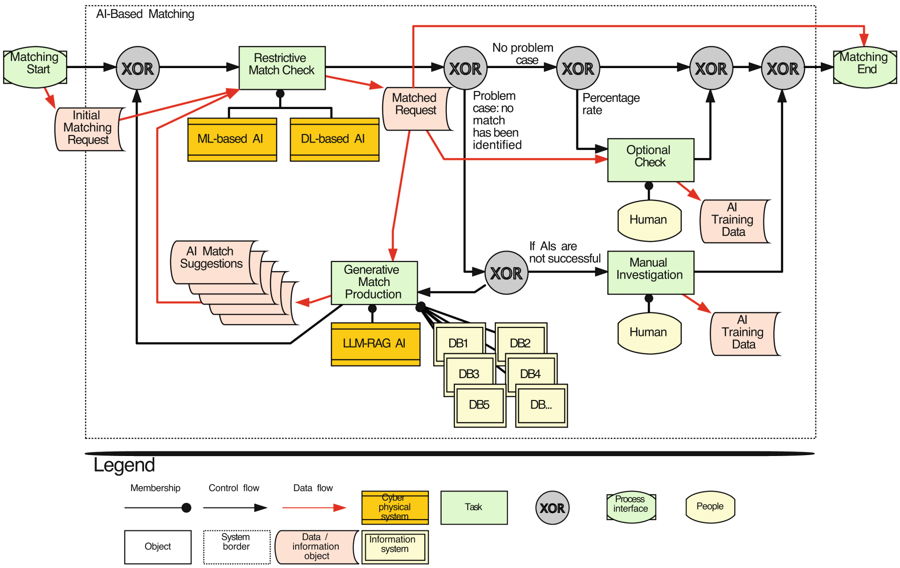

Fig. 1. Schematic cooperation of generative and restrictive AIs proposed for EM.

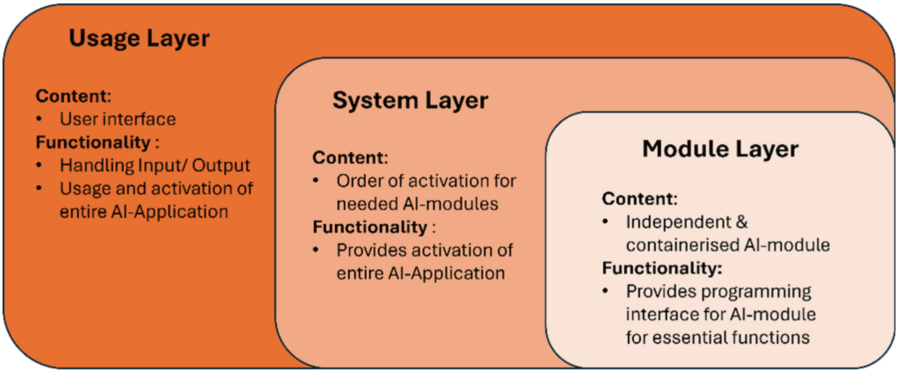

Fig. 2. Framework abstraction layers proposed for orchestrating arbitrary complex AI interplays, such as generative and restrictive AIs for EM.

The module layer contains independent, containerized AI applications, which are designed to solve a specific use case. These modules are built to operate autonomously and offer flexibility for different deployment scenarios. Each AI-module provides at least one command-line interface (CLI) script, which exposes its inner functionality to higher layers while specifying the expected input and output. This design allows for easy integration of AI capabilities without direct dependencies on other modules, enabling greater portability and scalability of the framework. The use of containerization via docker ensures that the environment for each AI-module remains consistent, minimizing compatibility issues across different systems. Also present in this layer are supporting nodes, which grant further functionalities to an individual AI-module (e.g. external computing, vector databases). The system layer plays an important role in managing and orchestrating the operation of the AI-modules. It can individually activate and control each AI-module, coordinating their interaction and ensuring that they function in the required sequence. This makes it the foundation of orchestrating the AI-modules, which are held in at least one activation script. These scripts define the order of execution, ensuring that dependencies between modules are respected. Furthermore, the system layer handles the management of input and output data for each AI-module, ensuring that data flows seamlessly between modules in a well-defined, daisy-chain-like process. This ensures that the overall system runs efficiently and that the output from one module serves as the input for the next in the sequence. In essence, the system layer functions as the "brain" that governs the behavior and interaction of all components, providing essential coordination and control. The usage layer acts as the interface for end-users, enabling them to interact with the underlying AI-modules without needing to understand the complexities of the system. It provides a user-friendly interface where input data can be entered, and output data can be retrieved. Users can select and activate specific orchestration scripts from the system layer, thereby selecting the sequence of operations to suit their needs. This layer is designed to be intuitive, ensuring that users can easily define the scope of the tasks they wish to perform with minimal technical knowledge. In addition, it offers mechanisms for monitoring and visualizing the execution of the AI-modules, providing feedback and insights into the system's performance. By abstracting the complexity of the lower layers, the usage layer ensures that the framework remains accessible to a wide range of users, from developers to non-technical stakeholders. The three-layered architecture of the framework provides a structured, modular approach that enhances both flexibility and maintainability. By clearly separating responsibilities across the module, system, and usage layers, the framework supports efficient AI integration, orchestration, and user interaction. While this layered design offers substantial benefits in terms of modularity, scalability, and ease of use, it also requires careful management of complexity and system overhead. As the framework evolves, it is essential to ensure that the interactions between layers remain well-defined, and that each layer continues to serve its intended purpose efficiently. Overall, this architecture enables the development of powerful, adaptable AI applications while providing an accessible interface for end-users, making it a robust solution for a wide range of use cases.

3.3 Infrastructural Architecture

While still upholding the abstraction layers on the software-side, the infrastructure of such a system is managed based on the Master-Slave-Architecture. This means the following: One node is in control of the whole traffic management of the system. Through the containerized software structure, each AI-module as well as other non-AI modules (e.g. databases, webservers, services) are represented as worker nodes. Hence, every component from the *Module Layer* and *Usage Layer* of the software architecture are worker nodes. The master node's duty is to orchestrate or rather manage the worker nodes. It thus can be located in the *System Layer* of the software architecture (see Fig. 3).

This combination of (a) *Master-Slave Architecture* and (b) *Layered Architecture* creates an adequate basis for a modular, efficient and scalable system. It combines the advantages form both models: The *Master-Slave Architecture* enhances the control and orchestration of distributed components, while the *Layered Architecture* ensures modularity, separation of functionality and ease of maintenance. Through the combination of these approaches and the strict containerization of each module, a robust framework for the creation of AI applications is provided.

4 Demonstration

The designed framework found its first use case in a real-world business setting. Here, AI models were created and deployed using the framework proposed. The general aim of this project is to verify a list of matches between object pairs based on their individual attributes. Hence, as part of this project, three AI models have been implemented. The first and second AI models cover two different approaches to verify these data pairs using DL and ML. The third AI model is an LLM-RAG which is responsible for suggesting new match possibilities. Due to the provided framework, these three models can be deployed and activated in cloud- or desktop environments. Further, they can be used by developers and non-technical stakeholders.

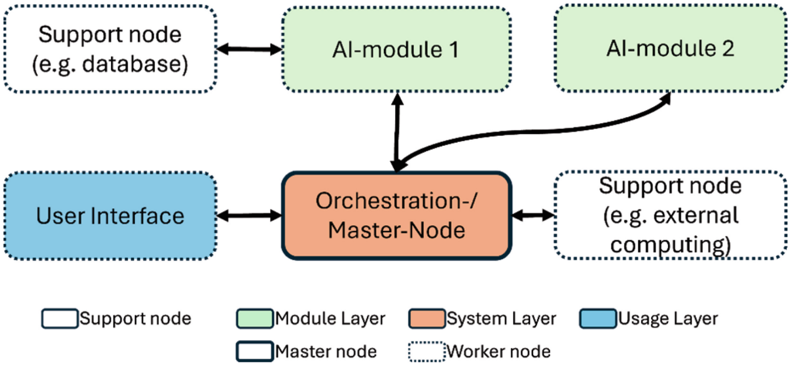

Fig. 3. Combination of software & infrastructural architecture proposed for modular, efficient, distributed and scalable AIs being orchestrated.

4.1 Project Setting

Lets assume to have a given list of data pairs. One data entry is inserted by an external user (now referred to as *user object*). The other data entry is provided as knowledge base (now called *system object*). Thus, the matching task refers to (1) classifying if the *user object* and the *system object* are the same (the match), and (2) if not matching, what alternative *system object* might match (the retrieving).

The knowledge base might refer to a collection of databases, such as company-specific data, internal databases or any external system connected (cf. the numbered database modeling elements in Fig. 1). Principally, the external system can have access to storage of almost every possible object.

However, due to missing or incorrect attributes of the *user object*, incorrect data matches can be generated in the matching process and due to the same reasons, the retrieval system can generate incorrect match suggestions, although taking an educated guess on which object might correctly match, which is based on the *user object* attributes.

4.2 Creation of Two Restrictive, Fuzzy Matching AIs

To counter the ER problem, two AIs with the task of verifying a data pairs have been created. One model uses a DL method whereas the second model uses a ML approach. Both models process a data pair and label it as correct (match) or incorrect (no match). When viewed from the framework's perspective, these AIs are worker nodes in the module layer.

Deep Learning-Based AI. The first AI model used a DL approach, which refers to an *artificial neural network* (ANN). It was created based on an open-source repository called "DeepMatcher" [39]. This repository contains a python package for the creation and training of ANNs, specifically for the task of matching two data objects. For the training of this ANN, around 10.000 verified data pairs were available. These were split up into training-, validation-, and test-dataset based on the method for creating ANN [32]. After training and a following validation, the results were evaluated with help of the test dataset in the first dataset. The second dataset shows the same network being run on a dataset 16 times as large. To fully meet the requirements of an AI-module in the framework, this AI-model must provide a programming interface, which grants access to the most essential functionalities. In the context of this model, this means the ability to train and activate an existing ANN. These interfaces refer to simple command-line interface scripts, which take in arguments from the command-line and direct them on the needed application points within the AI-model. Hence, these CLI-scripts lay above the current implementation of the AI-model, acting as a translator between software layers. Lastly, a docker image was built containing all requirements for running this AI-module. This ensured independence and modularity of this module.

Machine Learning-Based AI. The second AI model was developed using a ML approach called *Random Forest* (RF), an ensemble method that constructs multiple decision trees and aggregates their predictions for improved accuracy. For feature engineering, each attribute of the objects was represented as a vector using the sentence transformer model *'all-MiniLM-L6-v2'*. Additionally, the difference between the attribute vectors of one object and the corresponding attribute vectors of another object was calculated and included as part of the final feature vector. This combined feature vector was used to train the RF model to classify whether a match exists between the two objects. To be a fully functional AI-module, CLI-scripts have been laid above this AI model to ensure connectivity with neighboring layers. This interface is a complete replica to the DL AI matcher. This enables a further customization of the matching process depending on performance differences between models. If one AI module outperforms the other in one area of data, an instant change of AI module can be made. Additionally, this change does not effect other parts of the system. To further finalize this AI-module, a docker image was created containing the model and its requirements to ensure its independence and modularity.

4.3 Creation of a Generative, Fuzzy-Producing AI

A third AI model was developed using a *LLM-RAG* approach. The LLM-RAG differs from the two restrictive AI-modules presented in the previous section by having an entirely different task. Its task refers to the suggestion of new matching objects (*system objects*) for a given user object. Hence, a storage unit for available matching objects is needed as well as a retrieval system allowing the management and usage of this unit. In the context of the framework designed, this results in two worker nodes. One AI-module and one supporting node are granting usability to the AI.

LLM-RAG-Based AI. To set up a new object match generating AI, a few iterations of development have been realized. The fundamental task of this part was the vectorization of around 30 million data objects (*system objects*) and their retrieval based on some similarity search. Herefore, a developer friendly vector database technology named *ChromaDB* was firstly implemented. This enabled an initial and rapid development of needed functionalities and proved the concept. In this process, needed CLI-scripts have been developed. These make it a fully functioning AI-module in the frameworks perspective. However, with the amount of data needed to be vectorized and stored, the limit of *ChromaDB* was reached after a few million data entries. Hence, a migration to a more scalable vector database technology has been realized. The choice of storage technology fell to *MilvusDB*, which is an open-source, scalable vector database: It provides a huge set of possible adjustments for the storage and retrieval of vectors. This swift migration to another technology was enabled due to the designed modularity and interchangeablity of each module. Furthermore, existing CLI-scripts remained unchanged, creating no side effects for other modules due to this migration. An internal development for the vectorization was also achieved during his project. The choice of sentence-transformers fell on the *all-MiniLM-L6-v2* model, which proved great semantic representation of the context in the vector without having immense hardware requirements. The initial vectorization was computed on a standard midrange CPU, taking approximately 50 min for processing and storing 100.000 data objects. With the usage of a *CUDA*-capable GPU, this process reduced the processing time down to 2.8 min. Further optimization through efficient batching and storage into the vector database reduced the final processing time to 1.2 min per 100.000 data objects. This reduced the total processing time of 30 million data objects from 13 days down to 5.5 h.

Hereby, two new nodes can be identified: A supporting node containing the vector database, solely responsible for storing and searching the data, and an AI-module that handles the vectorization process and manages the vector database. An exemplary structure can be viewed in Fig. 3, where *AI-module 1* and *Support node* (e.g. database) form such cooperation. To summarize, four worker nodes are present in the current demonstration project: one DL node, one ML node as well as a pair of LLM-RAG nodes containing a vector database and its management or rather vectorization node. From a software perspective, all these nodes are covered by the Module Layer. To ensure the systems' usability for a wider range of stakeholders, nodes from the *System Layer* as well as from the *Usage Layer* have been added.

4.4 AI Orchestration and AI Component Orchestration

To enable comprehensive orchestration within the framework, an additional *Orchestration/Master* node and a *User Interface* node have been realized (cf. Fig. 3). This approach expands the system's accessibility from a technically skilled user base to a broader audience, while also introducing flexibility to adapt the system's functionality depending on the user's task.

In the project, the *Orchestration/Master* node was implemented as a *Flask-based backend*, leveraging its user-friendly design and seamless integration within the Python ecosystem. This backend exposes several *Application Programming Interfaces* (APIs), which enable the use of basic requests like querying processing status, file transfers and result provisions of AI outputs. The most important interface is the activation of an *AI Orchestration* script containing a predefined flow of AI-modules. It is visually modeled with help of the NMDL [31,32] and directly implements the AI cooperation design (cf. Fig. 1). It takes in a selected orchestration script by the user and activates the underlying docker run commands of the corresponding AI-modules. It easily can be extended to deal with multiple AI instances and realize load balancing and processing node-independent AI task realization [23], which supports the punctual and energy-efficient provision of AI results.

The backend is also part of the system: It provides and activates the orchestration scripts, while hereby being the storage location of all orchestration scripts. The *UI node* is represented with a *NGINX UI* webserver, which provides a custom frontend to a user. It handles the users data input and AI output. Further, it is responsible for the selection of the relevant orchestration script. The whole structure of this project can be viewed in Fig. 4.

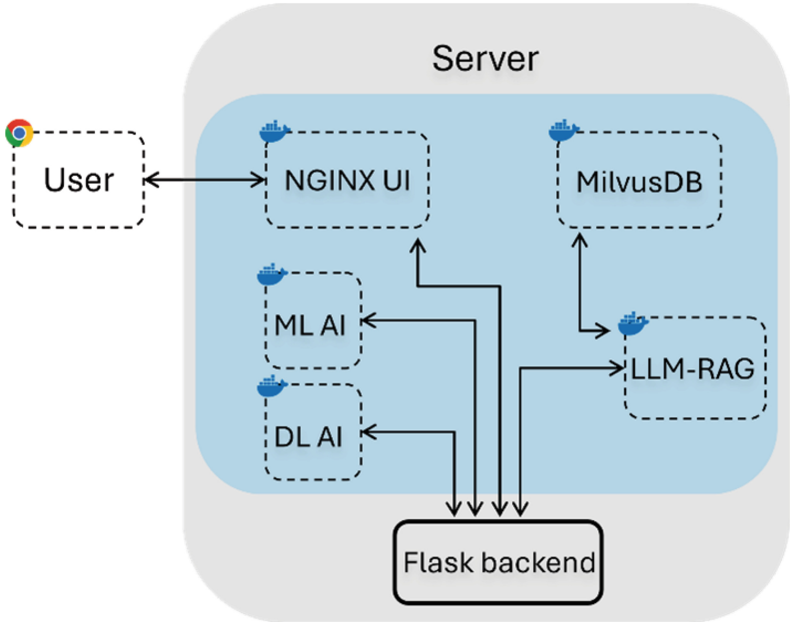

Fig. 4. Orchestration demonstration of the cooperating AIs for matching and retrieval.

In the figure, both software and infrastructure architecture can be clarified: From the software perspective, every node of the module layer (AI-modules and support modules) is presented as a docker container. This is visualized by a blue field in the figure. The orchestration node (represented by the *Flask backend*) of the system layer runs directly on the server. It is so separated from the blue field in the figure. However, the *Usage layer*, which consists of a browser session of a user, connects to the gray colored webserver. In this way, this architectural design accommodates multiple users, while catering to both technical and non-technical audiences.

Principally, when using this framework, users can choose between two orchestration script types: the first type is based on *docker-compose* and another type refers to a Python-based Docker script. The docker-compose option independently activates the ML and DL AI models to evaluate matches between given data pairs (*user object* and *system object*), whereas the Python script orchestrates a more complex, sequential activation of AI-modules.

From an architectural perspective, the AI workflow designed in Sect. 3.1, is realized as orchestration as follows (cf. Fig. 4): Initially, the restrictive matching AIs (ML and DL) verify the given data pairs. Any incorrectly identified match, where the *system object* does not align with the *user object*, is then forwarded to the LLM-RAG module. This module searches for alternative *system objects*, that are provided in the MilvusDB e.g. The new generated *system objects* are paired with the original *user object* to form an updated matching list. This list is subsequently re-evaluated by the DL or ML models. This process creates an interplaying AI system complex that continually refines and retrieves new matching pairs.

5 Evaluation

The proposed orchestration framework has been demonstrated by the interplay of two restrictive matching AIs and one generative retrieving AI and was assessed based on the requirements that have been elaborated in Table 1. In accordance with a design science-oriented research, the evaluation was conducted through a real-world business implementation, where AI models for fuzzy matching and retrieval were deployed in a structured workflow. Based on this demonstration example, the following checks the requirement fulfillment by using the same requirement numbering.

One of the core objectives of the framework was to ensure *modularity* (cf. Req. 1), allowing each AI-module to function independently while maintaining seamless integration with other components. The implementation demonstrated that the framework successfully achieved this goal. The containerized structure of the AI models, along with the system layer's orchestration capabilities, allowed easy *deployment* and *replacement* of individual modules without affecting overall system functionality. This capability was proven by a migration of vector database from *ChromaDB* to *MilvusDB*, where only the adaption of the module was needed. The usage of *command-line interfaces* enabled an uncomplicated and fast transition for other modules of the system. Additionally, these interfaces generally facilitate communication between layers, enabling smooth execution of predefined workflows. Further standardization of these interfaces could further enhance the *interchangeability* of each module. The software layers further clarify the different semantic node groups, clarifying the hierarchical structure and interaction of the whole system.

This containerized implementation also enables improved *scalability* (cf. Req. 2), which was another critical aspect considered during the evaluation. Through the creation and activation of multiple AI-module containers, workload can be processed individually. With the availability of further processing machines, load balancing can be used in the orchestration node. This distributes the workload of running containers across the available system, ensuring optimal performance.

The framework's ability to support large-scale vector databases was also examined, particularly in the case of the LLM-RAG model using MilvusDB. This addresses Req. 3. Results showed that vectorization and retrieval speeds significantly improved with GPU acceleration and optimized storage techniques. The time required for vectorizing 30 million data objects decreased from 13 days to 5.5 h, proving the effectiveness of the system in handling large datasets efficiently. Further expansions of the vector database infrastructure can be realized with *MilvusDB* as well. This makes LLM-RAG applications with up to 100 million vectors possible.

The framework was designed to be accessible to both technical and non-technical users. The inclusion of a Flask-based backend and a *NGINX* web interface enabled stakeholders to interact with the system without requiring direct command-line knowledge. The orchestration scripts being an algorithmic interpretation of the NMDL's ProcessView provided a structured approach to workflow automation, allowing users to activate specific AI pipelines depending on their needs. This approach enhanced the *usability* of the framework while maintaining flexibility in execution (cf. Req. 4).

Overall, the framework's robust and maintainable design supports rapid technology updates due to over-the-air updates (cf. Req. 5) - an essential advantage in the fast-evolving AI landscape. Additionally, employing this framework in a retrieval-based matching system significantly supported the mundane, time-consuming tasks performed by clerks. Due to the consequent training material completion and continuous AI refinement in trainings, the interplaying AIs can be managed and updated efficiently.

6 Discussion

This research is concluded below with a summary and critical result discussion.

Summary. This research has presented an orchestration framework that enables small and mediumenterprises to adopt AI-driven matching and retrieval systems, addressing a critical gap in accessibility to advanced automation tools. A real-world implementation demonstrated its efficacy, reducing vectorization time for 30 million data objects from 13 days to 5.5 h through GPU-accelerated optimization, underscoring its practical value in even handling large-scale tasks. The framework's design, emphasizes not only modularity, allowing enterprises to replace or upgrade AI components with minimal disruption. Numerous further requirements have been fulfilled, so that an effective problem solution can be proposed.

Critical Appraisal. The research question ("How can the complex task of data matching be supported by interplaying modular AI systems?") can be answered with regard to the following three: (1) the *modular software architecture*, (2) the *layered architecture abstraction* and (3) the *generative and restrictive AI cooperation* each of which is clarified in the following.

By integrating *modular software architecture* (module, system, and usage layers) with a master-slave infrastructure, the framework enables seamless deployment of containerized AI-modules—such as restrictive, fuzzy matching models (DL and ML) and a generative LLM-RAG system—while ensuring portability and scalability. The *layered architecture abstraction* simplifies user interaction, enabling both technical and non-technical stakeholders to orchestrate workflows via intuitive interfaces. Here, the NMDL shows strength to visualize workflows of cooperating AIs and humans. So, in a drag-and-drop manner, the design of the interplaying AIs can be constructed and interpreted by the framework algorithms. Thus, enterprises' lack of infrastructure, knowledge and resources to harness AI can be tackled by design, because the infrastructure is managed via containerized AI components automatically. The designed *interplay of generative and restrictive AIs* is exemplified for the complex task of matching and retrieval. In a ping-pong manner, restrictive AIs can be used to assess two text objects to be a match and function a kind of filtering system, and the generative AIs can be used to produce text objects to be a match given a text object, which are attractive to be filtered again. So, in a cyclic or iterative manner, the best match can be retrieved from a set of data bases.

Research Contributions. By bridging the gap between cutting-edge AI capabilities and enterprise resource constraints, this framework advances workplace sustainability by transforming labor-intensive processes into efficient, automated workflows. Further, this contribution does not only provide a technical blueprint for AI orchestration and its visual controlling by the NMDL's *ProcessView*, but also fosters equitable access to innovation in the rapidly evolving AI landscape. Beside the new kind of restrictive AI and generative AI interplay, a new approach for AI-based EM is proposed that advances contemporary ER research.

Limitations. While the framework effectively integrates modern AI technologies into existing processes, several limitations remain. The lack of labeled data prevented full automation, requiring manual intervention for certain tasks. Future work will focus on enhancing model generalizability through semi-supervised learning, reducing system complexity, and expanding accessibility features—such as life-cycle management interfaces—to further democratize AI adoption. Additionally, the current implementation does not support multi-user functionality going beyond single technical and non-technical users. This would demand further enhancements to the orchestration and back-end components to accommodate concurrent users, too.

Outlook. Future research will focus on improving AI model accuracy for the two restrictive and one generative AI presented. Further, it will focus on enhancing user accessibility: A key area of development will be expanding user-facing functionalities, such as introducing a training interface for AI models. This could evolve into a comprehensive data management system, enabling users to create, deploy, utilize, and manage AI models throughout their entire life-cycle. Furthermore, selecting or creating a standard structure for given CLI-scripts, would enable faster and more reliable implementations. These advancements will enhance the framework's capabilities, moving toward a fully automated and scalable solution for AI-driven orchestrated task realization, extending beyond the matching and retrieval tasks.

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A Hybrid Quantum-AI Architecture for Enhanced Blockchain Consensus

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Abstract. The increasing deployment of distributed infrastructures, such as satellite-based IoT networks and renewable energy microgrids, requires robust, secure, and efficient decentralized coordination mechanisms. However, traditional blockchain consensus protocols often face significant limitations in these resource-constrained settings due to inherent latency, computational overhead, and energy consumption, which hinders their practical adoption for real-time and mission-critical applications. To address this, we propose a conceptual hybrid consensus architecture. Our methodology employs formal concept analysis (FCA) to obtain a hypergraph representation from transaction data, followed by graph aggregation. The core of our validator selection strategy employs a recursive quantum approximation optimization algorithm (RQAOA), where a Reinforcement Learning (RL) agent adaptively provides parameters for the p = 1 QAOA steps. Security is further enhanced by Quantum Secret Sharing (QSS) for shared key generation among selected validators, while Proof of Elapsed Time (PoET) facilitates energy-efficient leader election. This synergistic integration aims to construct a resilient, secure, and resource-aware consensus mechanism suitable for dynamic and constrained distributed systems. We outline the system's design, detail the RQAOA procedure of finding a hypergraph minimal transversal for validator selection, and present an experimental setup with preliminary simulation results demonstrating the functional viability of the recursive pipeline. Although the framework shows potential, the consistent generation of high-quality parameters by the RL agent in this complex, sparse-reward RQAOA environment remains an active area for ongoing research and optimization.

Keywords: Blockchain Consensus · Validator Selection · Hybrid Quantum-Classical Systems

1 Introduction

Distributed infrastructures like satellite-based Internet of Things (IoT) networks and renewable energy microgrids demand secure, reliable coordination without centralized control. Blockchain technology provides a solution to trust and data

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integrity in these settings by maintaining a tamper-proof, decentralized operations ledger. In satellite communications, blockchain can enhance security and efficiency by eliminating single points of failure and ensuring that satellite data exchanges are transparent and immutable. [9] Similarly, in renewable energy systems, blockchain-enabled smart contracts can improve peer-to-peer energy trading and certify energy provenance, building confidence in distributed green energy markets [17]. However, integrating blockchain into resource-constrained or real-time environments is non-trivial due to the overhead of achieving consensus across distributed nodes. Consensus protocols, like Proof of Work, could incur latency and computational load, which is problematic for satellites and IoT devices with limited power and processing capabilities. Satellite nodes operate under strict energy and hardware constraints, and the time required to validate and append new blocks can obstruct real-time communications.

In IoT networks, the choice of consensus algorithm directly impacts power consumption and throughput, making it critical to use lightweight approaches suitable for small devices. Upadhyay et al. [20] note that a poorly suited consensus can drain battery-powered sensors or overwhelm low-bandwidth links. The distributed consensus protocol is often the main bottleneck that limits blockchain performance in IoT settings. Maintaining data integrity and node agreement under decentralization tends to compromise scalability and responsiveness. This problem hindered the adoption of blockchain for real-time control in renewable power systems, where fast feedback is essential [8]. As reported by Yu et al. [22], the low throughput of typical blockchains has been a barrier to their use in controlling renewable energy power systems (REPS). Researchers have begun exploring specialized and more intelligent consensus mechanisms tailored to constrained environments to resolve these issues. Delegated Proof of Stake (DPoS) is one approach that increases throughput by limiting the number of validating nodes; a recent study showed that combining DPoS with sharding significantly improved transaction rates in IoT data-sharing networks. The Proof of Task (PoT) mechanism in renewable energy was proposed to incorporate a control optimization problem into the consensus process. By having each node solve a local instance of a grid control task and then agreeing on the best solution, PoT effectively uses blockchain as a distributed computing platform to achieve real-time regulation. Consensus algorithms are evolving to leverage optimization using machine intelligence to meet domain-specific requirements.

This paper proposes a blockchain consensus mechanism enhanced with the Quantum Approximate Optimization Algorithm (QAOA) and Reinforcement Learning (RL). QAOA is a variational quantum algorithm that solves hard combinatorial optimization problems by alternating between problem-specific costs and mixing operations on a quantum state. It has the theoretical appeal that, at a sufficient circuit depth, QAOA can approach the optimal solution of an optimization problem. In practice, even shallow-depth QAOA can yield high-quality approximate solutions for certain tasks, making it attractive for improving consensus decisions, such as selecting an optimal subset of validator nodes or scheduling block producers. Using RL to tune the parameters of the

QAOA or guide its iterative process, one can outperform static quantum or classical heuristics with this synergy. Patel et al. [12] showed that an RL-enhanced QAOA scheme found better solutions to graph problems than QAOA or classical algorithms alone. Motivated by these developments, our approach integrates QAOA with an RL agent to form an intelligent consensus system. The intuition is that QAOA can efficiently explore the large combinatorial search space inherent in consensus. At the same time, RL can learn to adjust the parameters of the quantum circuit and decision policies in response to dynamic network conditions. The combination aims to produce a consensus that is fast, resource-efficient, and robust, properties desired in satellite IoT and renewable energy networks where both latency and reliability are critical. The following sections detail our proposed system's related work and architecture. Section 2 presents a focused review of related work relevant to lightweight consensus, quantum algorithms in blockchain, and RQAOA. Section 3 details the overall architecture of the proposed hybrid system and its constituent components. Our experimental setup and preliminary simulation results, which initially validate the proposed framework, are presented in Sect. 4. Finally, Sect. 5 concludes the paper and discusses future research directions.

2 Literature Review

This section first reviews the state of the art in lightweight consensus mechanisms suitable for resource-constrained environments and the emerging role of quantum and AI techniques in blockchain. Then it provides the validation rationale for the core components integrated into our proposed architecture.

2.1 State-of-the-Art

The deployment of blockchain in domains such as IoT and aerospace networks is driven by its potential to establish trust and data integrity without central authorities [9,21]. Smart contracts also promise to automate operations, potentially reducing latency [13]. However, inherent constraints of these environments, such as limited power, computational capacity, and intermittent connectivity, render traditional consensus protocols like Proof of Work (PoW) impractical due to their high overhead [15].

Consequently, research has focused on developing lightweight consensus algorithms. Intel's Proof of Elapsed Time (PoET) offers an energy-efficient alternative to PoW by using Trusted Execution Environments (TEEs) for random leader selection based on wait times [4]. Delegated Proof of Stake (DPoS) improves throughput by limiting block validation to a small set of elected delegates; Haque et al. [8] demonstrated significant performance gains by combining DPoS with sharding in IoT networks. Other approaches include reputation-based schemes and optimized Byzantine fault tolerance variants, as surveyed by Upadhyay et al. [20], who stress the need for algorithms tailored to IoT resource limits. For specific applications like renewable energy microgrids, Proof of Task (PoT) aligns consensus with operational goals by embedding grid control optimization into the validation process, enhancing real-time responsiveness [22].

Beyond classical optimizations, quantum computing and machine learning (ML) are being explored to enhance blockchain. While much quantum-related discussion centers on cryptographic threats, some works propose quantum-enabled consensus. Lin et al. [10] introduced Q-PnV, using quantum-generated randomness and entangled hypergraph states to improve security and fairness in consortium blockchains, indicating the potential of quantum modeling for consensus. Reinforcement learning (RL) has been applied to optimize consensus parameters dynamically. For instance, ML-driven approaches can adjust block sizes or propagation strategies to maximize performance under varying network conditions, as noted by Haque et al. [8] in the context of IoT.

The Quantum Approximate Optimization Algorithm (QAOA) is a promising hybrid quantum-classical algorithm for combinatorial optimization problems common in network optimization. Its potential for route planning and resource allocation has been explored. El Azzaoui et al. [2] demonstrated a blockchain-based QAOA for optimizing logistics routes, improving scalability, and reducing computation time. They also surveyed the applicability of QAOA to various Industrial IoT (IIoT) tasks, including supply chain management and energy distribution [5], often involving offloading hard optimizations to quantum services.

2.2 Validation Background

Our proposed architecture synergistically combines several techniques: Formal Concept Analysis (FCA), Recursive QAOA (RQAOA) assisted by reinforcement learning (RL), Quantum Secret Sharing (QSS), and Proof of Elapsed Time (PoET). The justification for exploring this combination comes from the individual strengths and the prior validation of these components in relevant contexts.

Formal Concept Analysis, as a mature mathematical framework, is well-established for deriving conceptual structures and identifying patterns from data. This makes it highly suitable for the initial stage of our pipeline, transforming raw transaction data into a meaningful hypergraph representation that serves as input for subsequent optimization processes. For the crucial task of selecting the validator, we employ RQAOA assisted by RL. The Quantum Approximate Optimization Algorithm (QAOA) has demonstrated its ability to tackle complex combinatorial optimization problems. In particular, Patel et al. [12] showed that an RL-enhanced QAOA scheme could outperform standalone QAOA or classical algorithms for graph problems by learning effective parameter-setting policies. This research strongly supports our approach of using an RL agent to guide the RQAOA parameters to solve the Minimal Transversal (MT) problem, which is central to our validator selection strategy. The recursive nature of RQAOA is designed to address larger problem instances by iteratively reducing them to manageable sizes.

To enhance security, particularly in key distribution among selected validators, our system incorporates Quantum Secret Sharing. QSS protocols leverage fundamental quantum mechanical principles, such as the no-cloning theorem and the properties of entanglement, to enable inherently secure key distribution. While the deployment of practical large-scale quantum networks is still an evolving field, the theoretical security guarantees offered by QSS are robust. The work of Lin et al. [10], which involved using entangled states to improve consensus mechanisms, also indicates the utility of quantum resources to improve the security aspects of blockchain systems. Finally, for energy-efficient leader election among the chosen validators, we integrate the proof of elapsed time. As discussed by Adhikari et al. [4], PoET is recognized for its significant energy efficiency compared to traditional PoW mechanisms, making it particularly well suited for resource-constrained nodes. Its reliance on Trusted Execution Environment (TEEs) to ensure the fairness and integrity of random wait-time generation provides a practical and secure mechanism for leader election with minimal computational overhead.

The aforementioned studies and principles provide evidence for the potential effectiveness of the individual techniques chosen for our hybrid consensus mechanism. FCA offers structured data representation; (RL-)QAOA provides a pathway for advanced optimization of validator selection; QSS offers a route to enhanced security for key establishment; and PoET enables energy-efficient leader election. Although these components have shown promise or have been validated in their respective specific contexts or for analogous problems, their synergistic integration into a unified blockchain consensus mechanism, as proposed in this paper, is novel. This body of existing research forms the basis for our hypothesis that their combination can lead to a resilient, secure, and resource-aware consensus protocol. The preliminary experimental results presented in Sect. 4 offer an initial exploration of this combined efficacy. We acknowledge that a comprehensive validation of this particular combination of techniques and their interplay is a crucial next step and will be the focus of continued research.

3 System Architecture

The proposed blockchain consensus mechanism integrates several classical, quantum, and machine learning components for efficient and secure block validation. The architecture is depicted in Fig. 1. The process begins in the Application Layer, handling user interactions or API calls that generate transactions. Once a block of transactions is ready, it triggers the Consensus Strategy Layer. This layer starts the consensus pipeline consisting of formal concept analysis (FCA), RQAOA, quantum secret sharing (QSS), and the PoET method. The sequence of interactions for block creation is shown in Fig. 3.

The pipeline starts with the FCA layer for hypergraph generation. Incoming transactions are pre-processed and analyzed using FCA to identify inherent structures and relationships between participants. These relationships form the basis for an initial hypergraph H_{fca}. H_{fca} is aggregated into a smaller hypergraph H_{agg} based on clustering of nodes and priority metrics to manage computational complexity. This aggregation step yields H_{agg} and the aggregation mapping of the original nodes. The aggregated hypergraph H_{agg} makes an input for the next stages.

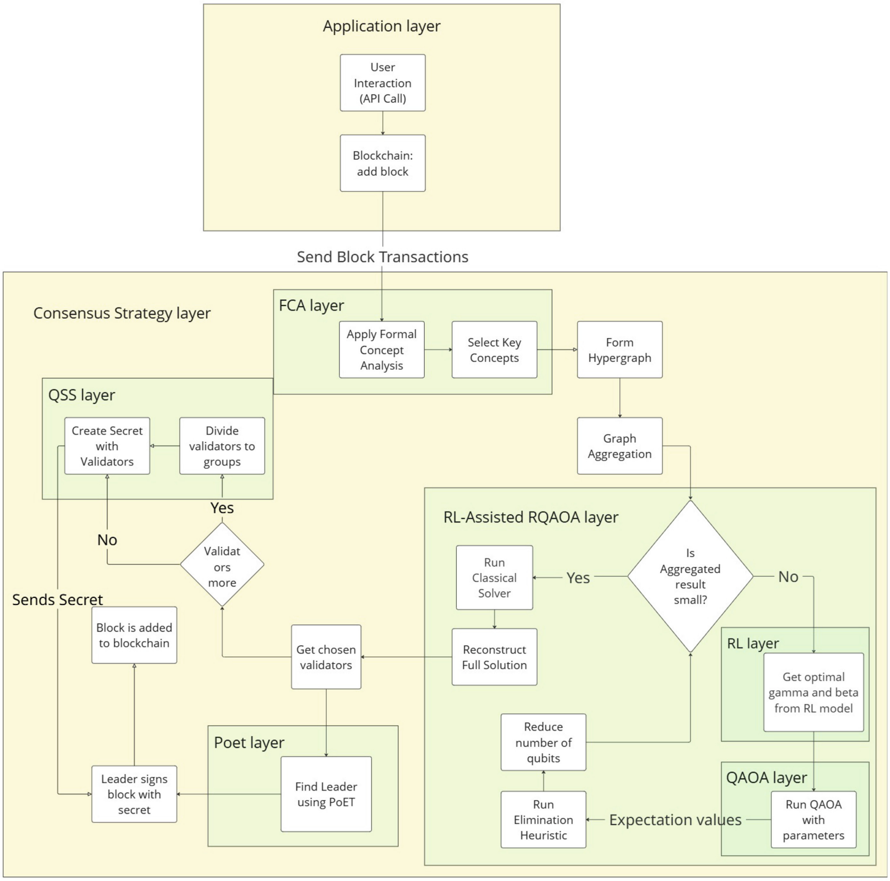

Fig. 1. System Architecture Diagram showing the interaction between Application, Consensus Strategy, and underlying layers during block processing.

The selection of the core validator is performed by the RL-Assisted Recursive QAOA (RQAOA-MT) stage, which aims to find a Minimal Transversal (MT) of H_{agg}. RQAOA iteratively simplifies the MT problem by running a p=1 QAOA subroutine at each step k. A pre-trained reinforcement learning agent (RL) provides the trial parameters (γ_k, β_k) for this p $= 1$ QAOA, receiving the characteristics of the current state s_k (derived from H_{agg} and the progress of the RQAOA) as input. The agent's policy value network (Eq. 1) generates a policy over QAOA angles, trained to minimize a PPO-style loss (Eq. 2). The cost Hamiltonian H_C for the MT on n qubits (nodes of H_{agg}) is given by Eq. 3.

$$(\text{policy\_params}(s_k;\theta), V(s_k;\theta)) = \text{NN}(s_k;\theta) \tag{1}$$

$$L(\theta) = E_t[L_t^{\text{CLIP}}(\theta) - c_1(V(s_t;\theta) - G_t)^2 + c_2 S[\pi_\theta](s_t)] \tag{2}$$

$$H_C = \sum_{i=1}^{n} \alpha \frac{I_i - Z_i}{2} + \sum_{e \in E_{work}} \beta_{penalty} \prod_{j \in e} \frac{I_j + Z_j}{2} \tag{3}$$

In Eq. 3, the first term (weight α) minimizes selected nodes (qubit state $|1\rangle$, $Z_i = -1$), and the second (weight $\beta_{penalty}$) penalizes uncovered hyperedges e in H_{agg} (where E_{work} is its edge set). The standard mixer $H_M = \sum_j X_j$ is used. At each RQAOA step k, the p=1 QAOA prepares the state:

$$|\psi_1(\gamma_k, \beta_k)\rangle = e^{-i\beta_k H_M} e^{-i\gamma_k H_k} |+\rangle^{\otimes n_k} \tag{4}$$

The expectation values $\langle Z_i \rangle_k$ are calculated using a Qiskit Estimator. A hybrid elimination heuristic then selects a qubit j to fix (max $|\langle Z_j \rangle_k|$), and its Z_j operator is replaced by $\text{sgn}(\langle Z_j \rangle_k) I$. The Hamiltonian H_k is reduced to H_{k+1}. This recursion repeats until H_k has $\leq n_{final}$ qubits (e.g., 3 qubits), then solved classically. The full solution is reconstructed by backtracking and then unaggregated to form the candidate validator set, V_{cand}. This RQAOA-MT procedure is visually described in Fig. 2.

Two subsequent layers process this validator set. Following the selection of the validators by RQAOA, the QSS layer facilitates the secure generation and distribution of a shared secret among the participating candidate validators. This utilizes principles of quantum mechanics to ensure security against eavesdropping. Our simulated approach involves preparing and distributing a multi-qubit entangled state, such as the n-qubit Greenberger-Horne-Zeilinger (GHZ) state, among the $n = |V_{cand}|$ validators:

$$|GHZ_n\rangle = \frac{1}{\sqrt{2}}(|0\rangle^{\otimes n} + |1\rangle^{\otimes n}) \tag{5}$$

This helps the dealer or the participants to establish a shared secret key collaboratively. By performing coordinated local measurements on their respective qubits in randomly chosen bases, the validators can agree on a secret bit string. The security relies on quantum principles like the no-cloning theorem and the fact that any attempt to intercept and measure the distributed qubits would inevitably disturb the entanglement, revealing the presence of an eavesdropper. Specific protocols can implement threshold schemes where only subsets of validators of a certain size k (out of n) can reconstruct the secret. During QSS, the PoET Layer performs a leader election among the candidate validator set. The core mechanism involves each validator running a certified PoET code within its secure TEE enclave. First, the validator requests a timer, and the enclave securely generates a random wait time T_{wait}. The TEE guarantees randomness and prevents tampering with this timer. Subsequently, the enclave creates an

```
BEGIN_RL_RQAOA_EXECUTION:
    Input: H_initial_agg (Aggregated Hypergraph for Hitting Set)
    Input: rl_agent (Optional Pre-trained Reinforcement Learning Agent for p=1 QAOA parameters)
    Input: n_final_threshold (Integer threshold for switching to classical solver)
    Input: qaoa_interface (Object to execute QAOA p=1 and get expectation values)
    Input: classical_solver (Function to solve small Hamiltonian problems exactly)
    Input: reduction_heuristic (Function to choose which variable to eliminate)
    Input: hamiltonian_reducer (Function to create a new, smaller Hamiltonian)
    Input: solution_reconstructor (Function to build the full solution from eliminations)

    H_current ← BuildCostHamiltonianForHittingSet(H_initial_agg)
    n_qubits_current ← GetNumberOfQubits(H_current)
    elimination_history ← EmptyList // Stores (original_node_id, fixed_spin_value) for reconstruction
    current_qubit_map ← GenerateInitialQubitToNodeIDMap(H_initial_agg)

    LOOP while n_qubits_current > n_final_threshold:
        current_rl_state s_k ← GetStateForRLAgent(H_current, k, current_qubit_map)
        (gamma_k, beta_k) ← rl_agent.predict_p1_qaoa_parameters(s_k)

        // QAOA p=1 Execution and Expectation Value Calculation ---
        expectation_values E_k ← qaoa_interface.get_expectations(H_current, gamma_k, beta_k)

        (qubit_to_fix_local_idx, fixed_spin_value, original_node_id_eliminated) ←
            reduction_heuristic.choose_variable_to_eliminate(E_k, current_qubit_map)

        Append (original_node_id_eliminated, fixed_spin_value) to elimination_history

        (H_next, next_qubit_map) ←
            hamiltonian_reducer.reduce_hamiltonian(H_current, current_qubit_map,
                                                   qubit_to_fix_local_idx, fixed_spin_value)

        H_current ← H_next
        current_qubit_map ← next_qubit_map
        n_qubits_current ← GetNumberOfQubits(H_current)
    END LOOP

    final_solution_for_small_problem ← classical_solver.solve_ising_ground_state(H_current)

    full_solution_map_original_nodes ←
        solution_reconstructor.reconstruct_full_solution(final_solution_for_small_problem,
                                                         elimination_history,
                                                         current_qubit_map,
                                                         GetOriginalNodeIDs(H_initial_agg))

    selected_chunks_for_hitting_set ←
        ConvertSpinMapToSelectedNodeSet(full_solution_map_original_nodes)

    RETURN selected_chunks_for_hitting_set
END_RL_RQAOA_EXECUTION
```

Fig. 2. Pseudo-code of the RL-Assisted RQAOA for Minimal Transversal (RQAOA-MT) algorithm.

attestation, a digitally signed certificate containing the generated wait time and proof that it originated from certified code within the trusted environment. The node then waits for the duration T_{wait} specified in the certificate, a process designed to consume minimal CPU resources. Upon expiration of the timer, the node broadcasts its certificate to the network.

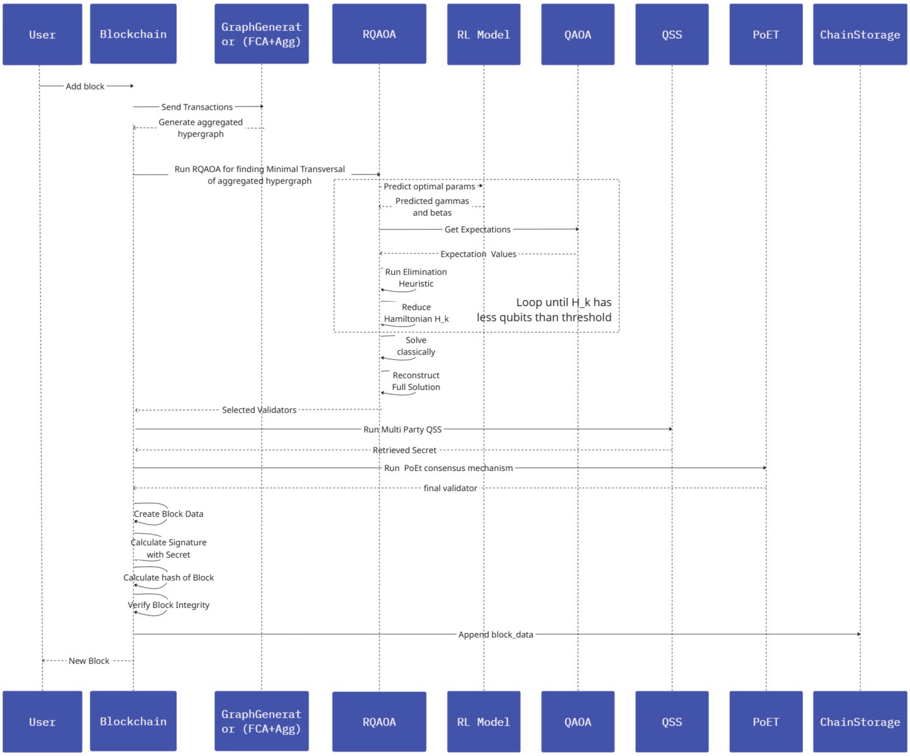

Fig. 3. Sequence Diagram illustrating the block addition process using the FCA, RQAOA, QSS, and PoET consensus method.

Other participating nodes receive these certificates from potential leaders. They verify the authenticity and integrity of each certificate using the TEE's remote attestation mechanism. The validator L who presents the valid certificate corresponding to the shortest verified wait time is then elected as the leader for the current consensus round, according to the selection rule:

$$L = \arg \min_{v \in V_{cand}} \{T_{wait,v} \mid \text{Verify}(C_v) = \text{True}\} \tag{6}$$

This simulation-based approach provides a leader election mechanism with low energy consumption compared to PoW, making it suitable for resource-constrained nodes, while its security relies on the integrity of the underlying TEE hardware and the associated attestation infrastructure. Our system simulates this process by assigning random wait times to the validators V_{cand} and selecting the one with the minimum time as the final validator. Finally, Block Finalization combines the leader, global secret, transactions, and metadata. Cryptographic signatures and hashes are computed and verified before the block is appended to the blockchain.

4 Experimental Setup and Preliminary Results

To provide an initial proof-of-concept for the proposed hybrid consensus mechanism and gather preliminary performance insights, we performed simulations focusing on the RQAOA-MT component for the selection of the validator. The performance of our FCA+RQAOA approach was compared with a classical baseline, LCM + SHD, in batches of real-world Ethereum transaction data [1].

For each training and evaluation instance, transactions from one or more blocks were accumulated until the derived FCA hypergraph (H_{fca}) contained approximately 200 unique participants. This H_{fca} was then aggregated to H_{agg} (typically $4 - 10+$ chunks) using a priority-based method, which served as input for RQAOA-MT. The RQAOA recursion continued until the problem was reduced to a threshold of 3 qubits.

Our FCA+RQAOA approach utilized the RQAOA-MT algorithm (Fig 2) with a QAOA subroutine of p = 1. The parameters (γ_k, β_k) were predicted by a PPO-based RL agent (Sect. 3). A hybrid elimination heuristic was employed: trying to fix variables if $|\langle Z_i \rangle_k| \geq 0.8$, otherwise defaulting to fixing the variable with maximum $|\langle Z_i \rangle_k|$. The baseline LCM + SHD involved applying LCM [19] to find frequent closed itemsets, forming a hypergraph, and then using an SHD algorithm [11] to find its MT. Quantum simulations used Qiskit Aer.

We evaluated both methods on 50 distinct transaction batches. The key metrics included the final number of selected validators, core computation time, and potential TPS. Table 1 summarizes the aggregated results. The conceptual data for PoW, PoS, and DPoS regarding validator counts, block time, and TPS are drawn from established literature and publicly available network statistics [3,6,7,14,16,18].

The preliminary results presented in Table 1 are encouraging. Our FCA+RQAOA approach achieved a high validity rate, with 94.0% of the processed instances resulting in solutions with zero violations in the original transaction hypergraph H_{fca}. A key finding is the significant reduction in the average number of selected validators: 8.04 ± 15.12 for valid RQAOA runs compared to 226.04 ± 122.78 for the baseline LCM+SHD. This indicates that our method consistently finds much more compact validator sets, which is highly beneficial for reducing communication overhead in subsequent consensus stages such as QSS and PoET.

Table 1. Summary Comparison of Consensus Methods. Conceptual data for PoW, PoS, and DPoS from the literature.

Method	Avg. Validators	Avg. Block Time	Potential TPS
LCM+SHD	226.04 ± 122.78	0.0404	4637.4
FCA+RQAOA	8.04 ± 15.12	0.2667	1727.5
PoW (Typical)	$\sim 10 - 20$ (Pools)	$\sim 10 - 60$ min	$\sim 3 - 15$
PoS (Typical)	$\sim 100s - 1000s+$	$\sim$ 10 s - 15 min	$\sim 100s - 1000s+$
DPoS (Typical)	$\sim 20 - 100$ (Deleg.)	$\sim 1 - 60$ s	$\sim 1000s - 4000+$

Although the average execution time for the FCA+RQAOA pipeline is currently higher than that of the purely classical LCM+SHD approach, this is largely attributable to the iterative nature of RQAOA and the overhead associated with simulating quantum circuits. Despite this, the system demonstrates a substantial potential TPS of 1727.5. While this TPS is lower than that of the LCM+SHD baseline, it compares favorably with the performance of established consensus mechanisms such as PoW and is competitive within the range of many PoS and some DPoS implementations, as indicated by the comparative data of Table 1. These initial results serve as a proof-of-concept, demonstrating the viability of the proposed hybrid architecture.

5 Conclusion

This paper introduced a hybrid blockchain consensus mechanism designed to address the security, efficiency, and resource constraints prevalent in distributed systems such as satellite IoT networks and renewable energy microgrids. Traditional consensus protocols often struggle in these environments due to high latency, computational demands, or energy consumption. Our proposed architecture integrates FCA, RQAOA, QSS, PoET, and RL to create a potentially more efficient consensus pipeline.

The core contribution lies in the synergistic combination of these techniques. FCA provides a structured way to extract meaningful relationships from transaction data, creating a hypergraph ($H_f ca$). This hypergraph is then aggregated to reduce its scale for the subsequent optimization task. RQAOA, with an RL agent adaptively providing parameters for its p=1 QAOA steps, then tackles the combinatorial challenge of selecting a compact validator set by finding a Minimal Transversal of the aggregated hypergraph. Then, QSS generates a shared secret key with a validator set for block finalization, while PoET provides a mechanism for electing a leader from the validator set.

Preliminary simulations, detailed in Sect. 4, focused on validating the initial stages of this synergistic pipeline, specifically the FCA and RQAOA-RL components for the selection of the validator. A key finding was the significant reduction in the average number of selected validators to 8.04 ± 15.12 in valid runs, compared to 226.04 ± 122.78 for the classical baseline LCM+SHD. This compactness is highly beneficial for reducing communication overhead in the subsequent conceptual QSS and PoET stages. Although the simulation of quantum components resulted in a higher average execution time (0.2667 s) for this selection stage compared to the classical method (0.0404 s), the potential TPS of 1727.5 is substantial and compares favorably with several established consensus mechanisms.

These promising findings from the RQAOA-RL pipeline, underscore the potential of the overall hybrid architecture. Such efficiencies in validator selection are crucial for better resource utilization and directly benefit the conceptual subsequent stages, like QSS and PoET. The broader vision for this integrated system includes enhanced security from quantum-based key sharing and improved overall system efficiency with low computational overhead from components like PoET. However, realizing this full potential depends on addressing the primary challenge highlighted by our preliminary results: the robust optimization of the RL agent to consistently guide the RQAOA process toward high-quality solutions in diverse graph structures, particularly by enhancing the signal strength of the QAOA steps p = 1.

Beyond this challenge of optimizing the RL agent for RQAOA, the integration of multiple complex components inherently increases the complexity of the system and introduces other considerations. The overall effectiveness of the RQAOA-MT approach remains sensitive to the chosen elimination heuristic, along with the aforementioned QAOA parameters. Furthermore, the practical deployment of the QAOA and QSS components depends on the availability and maturity of quantum hardware or the efficiency of their classical simulation, which currently remains a bottleneck for large-scale problems. The scalability of the FCA, graph aggregation, and QSS grouping mechanisms also requires further dedicated research for larger networks.

Future work will focus on: Extensive training and hyperparameter tuning of the RL agent for RQAOA. Implementing and comparing different RQAOA elimination heuristics. Comprehensive benchmarking against existing consensus mechanisms on larger datasets to quantify performance in terms of validator set quality, overall consensus time, and resource usage.

In conclusion, the proposed framework leveraging RQAOA guided by RL, integrated with FCA, QSS, and PoET, offers an innovative pathway towards intelligent, secure, and resource-efficient blockchain consensus protocols, with preliminary results supporting its feasibility and potential.

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Short Papers

Engineering Functional Requirements

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Abstract. Requirements Engineering (RE) is a critical sub-field of engineering that deals with identifying, analysing, specifying, modelling, and validating the user needs and constraints for a system. This not only holds for Software Engineering (SE) but for engineering in general (e.g., for building bridges and other artefacts as well). In our view, the main development line for the Engineering of *Functional* Requirements (EFR) should be:

EFR –> Conceptual Model –> SE

So, EFR should result in a conceptual model as a basis for the software to be built. Although this line might look 'waterfall-like', it can equally apply to each individual increment in an incremental development approach.

We argue that the result of EFR should be an implementation-independent *conceptual model* (CM) that models both the *statics* and *dynamics*, and we show that such a CM can form a solid base for SE. We work out how such an implementation-independent CM can be developed and looks like, covering both the static and the dynamic functional requirements *in an integrated way*.

Results: A theoretically sound and concrete conceptual model that catches and integrates the static *and* dynamic functional requirements. The model forms a solid base for SE. It results in a traceable development line from EFR to SE.

Keywords: Requirements engineering · functional requirements · conceptual model · statics · dynamics · development path · software engineering · software design

1 Introduction

This overview paper concentrates on the *functional* requirements of a system to be built, not on its quality (or 'non-functional') requirements. In general, quality requirements follow a different route.

We start from *textual* Conceptual Models. Texts are closer to software (being text) than diagrams, but diagrams might be easier for people to understand. So, the systematic mappings to Natural Language and to graphical Conceptual Models in [1] might help for validation with the user organization (v1 and v2 in Fig. 1). In Fig. 1, the EFR block and its arrow are dashed, while the other blocks and arrows are rigid, because those steps are more straightforward.

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The Conceptual Model (CM) of a system should model the *statics* as well as the *dynamics* of the system. The *statics* can be specified by a Conceptual *Data* Model (CDM) and the *dynamics* by a Conceptual *Process* Model (CPM); see Fig. 2. A CDM consists of one data model, exactly specifying the states the system can possibly be in, while a CPM consists of several (usually *many*) ‘interaction descriptions’, i.e., descriptions of interactions with the system, e.g., by use cases or sequence diagrams.

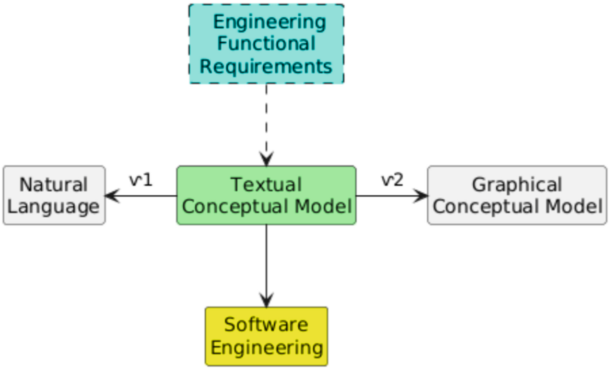


Fig. 1. The position of Requirements Engineering, Conceptual Model, and Software Engineering w.r.t. *Functional* Requirements (including some validation options)

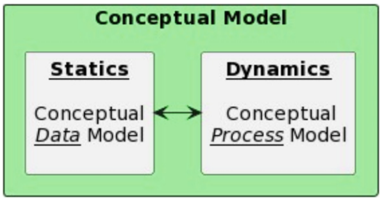


Fig. 2. Conceptual Model $\equiv$ CDM $\oplus$ CPM

We emphasize that the static aspects and dynamic aspects of a system should be aligned: It is not enough to develop static models only or dynamic models only, and not even to develop both as two separate worlds. The Conceptual *Data* Model and the Conceptual *Process* Model must be aligned and consistent with each other, as explained and illustrated in Sect. 2.3. They are the two sides of the same coin!

The Computation-Independent Model of the Model-Driven Architecture (MDA) approach defined by the Object Management Group (https://www.omg.org/mda/) is more or less on the same level as our CM-notion. A Computation-Independent Model is a high-level representation of business requirements, goals, and rules without any details about the system's implementation.

2 Conceptual Model Must Describe Statics *and* Dynamics

A Conceptual Model must describe the static and the dynamic functional requirements *in an integrated way*. Section 2.1 treats the dynamics of a system, Sect. 2.2 its statics, and Sect. 2.3 their mutual dependency and consistency.

2.1 Dynamics: Developing a Functional Requirement

This section describes a (potential) journey when developing a Functional Requirement.

Developing a Functional Requirement could start with an elementary **User Wish** [1], for instance to *Register a student*. The User Wish could then be transformed to a **User Story** by introducing a user role and (optionally) a benefit part [2]. For example:

As an administrator, I want to Register a student *so that (s)he can follow a study.*

However, a user story is simply not enough as an EFR end result. Much more requirements analysis still needs to be done. A software engineer might think that that is enough to 'fill in the blanks' him- or herself, but that probably leads to functionality decisions 'hidden in the software' which, moreover, might also be wrong (which might be unnoticed, initially)! The User Wish or User Story could be worked out into a Use Case: A **Use Case** is a text in natural language that describes a sequence of actions in a typical usage of the system and should describe one session with the system [3–5]. A use case roughly corresponds to an *elementary business process* in business process modelling [5, 6]. A use case can be developed incrementally by first working out its Main (Success) Scenario (MSS) and then add individual Alternative Scenarios (AS) and extensions later on. For example, the MSS of *Register a student* could be as follows:

1. The administrator asks the system to *Register a Student*.
2. The system asks the administrator for the student's name, address, birth date, and phone number (if any).
3. The administrator provides the system with that info.
4. The system generates a new, unique *student number*.
5. The system registers the student with the provided info and the generated student number.
6. The system informs the administrator about the generated student number.

A Use Case can be rewritten into a *textual* **System Sequence Description** (tSSD). A tSSD is a kind of stylised Use Case which schematically depicts the tasks of and interactions between the user, the system (as a black box), and other actors (if any), including the messages between them. As an illustration**,** the tSSD of our sample use case could be (with A standing for 'administrator' and S for 'system'):

1. A -> S: Register a Student.
   S -> A: 'What is student's name, address, birth date, and maybe phone number?'
2. A -> S: that info.
3. S: generate a unique student number.
   S: register the student with the provided info and the generated student number.
4. S -> A: the generated student number.

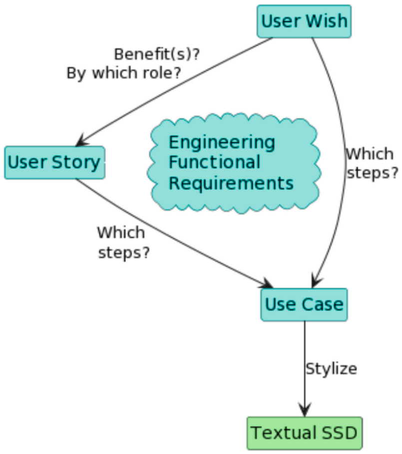


Fig. 3. Development steps for functional requirements

The step via a User Story might be skipped. Figure 3 summarizes the foregoing.

In [1, 7], a general grammar for tSSDs is presented, while [8] gives a formal semantics for the tSSD-constructs. Moreover, it gives rules to map tSSDs to *natural language* (English in this case) and rules to map them to *sequence diagrams*. We also constructed rules to map such tSSDs to *activity diagrams* and rules to map tSSDs to *BPMN diagrams* [9]. The natural language equivalents and diagram equivalents might be useful for validation, and later on for explanation and for documentation as well. See Fig. 4:

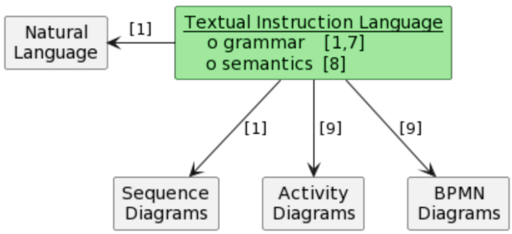


Fig. 4. Validation opportunities and relevant publications

A tSSD (being on conceptual level) can be transformed to software procedures, e.g., to *(stored) procedures* in case of a DBMS (Database Management System) based on SQL, see [1], or *methods* in case of an object-oriented system, see [10]. For more background on DBMSs, see [11]. For useful design patterns for object-oriented software, see [12].

The development path for a Functional Requirement is summarized in the left column of Table 1, where the blue part indicates the Requirements Engineering realm, the green part the conceptual level, and the yellow part the Software Engineering realm. The statics part (the right column of Table 1) is explained in Sect. 2.2.

Table 1. The development paths

Dynamics / Processes (what the System must **do**)	**Statics** / Data structures (what the System must **know**)
elementary User Wish	Domain Models*
↓	↓
User Story	↓
↓	↓
Use Case (= MSS + AS*)	↓
↓	↓
tSSD	Conceptual Data Model
↓	↓
SW procedures	SW Data Model

*: zero or more

2.2 Statics: Developing the Conceptual Data Model

Usually, a data model can start small and simple as a **Domain Model**. A Domain Model might initially only contain **concepts** and their **associations**, to be extended (later) with the **properties** of the concepts and the **multiplicities** of the associations. The data model may grow during the development of the functional requirements.

To reach a full-fledged **Conceptual Data Model** from a Domain Model, each many-to-many association must be transformed into a few many-to-one associations, references must be made explicit, uniqueness properties must be added, and per property it must be indicated whether a value is required or optional. Moreover, the possible values per property must be determined and there might be some remaining (integrity) constraints to be added as well [1]. So, a Conceptual Data Model is not only about entities, their status, and their relationships, but also includes the relevant properties of the entities, the possible property values, and all kinds of constraints on the data.

The Conceptual Data Model can then be transformed to a data model in software. This could be a class diagram in case of an object-oriented system or a database schema consisting of tables and constraints in case of a relational DBMS with SQL, for instance. The right column of Table 1 shows the development path for a data model.

2.3 Statics and Dynamics: Their Mutual Dependency and Consistency

The Conceptual Process Model (say, all the tSSDs) and the Conceptual Data Model depend on each other and must be consistent with each other! Below, we mention a few general, ubiquitous situations of dependencies and potential inconsistencies. (But there will be much more dependencies and potential inconsistencies.)

A typical situation for coordination between the statics and dynamics is the case of the *creation* of an instance: A tSSD for creating an instance of a concept will already suggest properties of that concept, which should then appear in the CDM as well (see the tSSD-example in Sect. 2.1). On the other hand, maybe that concept might already possess other properties in the CDM as well. Should the Create-procedure be adapted to add those other properties too? Maybe, but maybe that can only be done in a later business process stage. This would imply that values for those other properties should be *optional* in the CDM. As an illustration, the tSSD *Register a Student* in Sect. 2.1 already suggests a concept *Student* with properties *student number*, *name*, *address*, *birth date*, and *phone number*. But maybe the concept *Student* in the Conceptual Data Model (CDM) also has a property *nationality*, because that is also relevant for the user organization (say, a university). So, shouldn't *Register a Student* be adapted, adding *nationality* to Step 2? The user organization may say that that will be done in a later stage. This implies that a value for *nationality* should be optional in the CDM (and that some use case *Add the nationality to a registered Student* should be added).

Another typical situation of coordination between the statics and dynamics is in the case of *deletion*: When an instance has to be deleted, what about instances of other concepts (or the same concept) that according to the CDM might refer to the instance to be deleted? Should those instances also be deleted (a so-called *cascading delete*), or should the deletion be refused? The answer from the user organization might be subtle.

For example, an *order* might get associated with it *reservations of resources* (e.g., products, machines, workers, etc.) when the order still has to be executed and gets *(intermediate) results* if it is (being) executed. As will follow from the constraints on the data, formulated in the CDM, deletion of an order cannot be unconditionally or in isolation. When the order still has to be executed and has no *(intermediate) results*, the order and all its *reservations of resources* might be deleted (a *cascading delete*). However, when the order has (intermediate) results, the order cannot be deleted anymore. The procedure to remove an order could then be (in our pseudo-code):

```
define remove order x as
 if order x has no (intermediate) results
  then delete all x-related reservations of resources;
       delete x
  else return <message>
 end
```

Hence, due to constraints in the CDM, the procedure to remove an order becomes a removal *attempt*. In general, due to constraints in the CDM (*statics*), it could be that a procedure (i.e., *dynamics*) must be adapted:

```
define <procedure> as
 if no static constraints are violated
  then do as intended
  else return <message>
 end
```

So, still some additional Requirements Engineering work might be necessary in order to make the statics and dynamics consistent with each other.

3 From Conceptual Model to Software

While SQL has all kinds of language constructs to specify constraints (e.g., keys and foreign keys), imperative programming languages usually lack such constructs. De Brock and Smedinga [10] outline how constraints specified in the Conceptual Data Model can be worked out systematically in an OO-environment.

The book [1] explains in depth how to come all the way from *elementary user wishes* and simple *domain models* to a *conceptual model* (*data* as well as *processes*), and from there to an implementation in a relational DBMS using SQL. The development paths are straightforward and increase transparency and traceability (forward *and* backward traceability). For more background on traceability we refer to [13, 14].

In [10] it is also explained how to come from a *conceptual model* (*data* and *processes*) to an OO-implementation, illustrated by an extensive example.

The implementation of the conceptual model could be on another (old, current, or new) technology instead; see Fig. 5. As an example, [1] also sketches (a) an implementation using (paper) notebooks and (b) an implementation with parchment scrolls (old 'write once' data storage devices), quill pens ('write-heads' for scrolls), slates ('rewritable memory'), slate pencils ('write-heads' for slates), and sponges (to 'reset' slates).

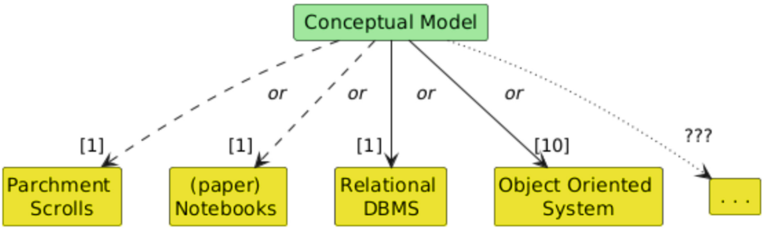
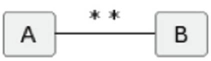
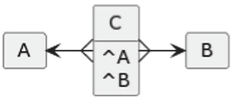


Fig. 5. A Conceptual Model must be implementation-independent

4 Some Differences Between the RE-Scope and the SE-Scope

As an illustration, we give a few examples of potential misunderstandings regarding what belongs to EFR and what to SE. For instance, a many-to-many association in a Domain Model or Entity-Relationship Model can be transformed in a 'mechanical' way into a few many-to-one associations, namely as follows:

Transform  into 

where C represents a new concept and ^A and ^B represent references from C to the concepts A and B. It might seem that with delivering a many-to-many association, EFR has done its job and SE can take over. However, this is not enough as an end product of

EFR. E.g., what is a unequivocal name for concept C, which uniqueness constraint(s) must hold for C, and which other properties belong to C? The combination of ^A and ^B is unique, one might guess. However, a particular A and a particular B might be 'associated' more than once, cf. the many-to-many association *Student enrolls for Course* (A = *Student* and B = *Course*), where a student can enroll for a course more than once. Hence, in this case, the combination of ^A and ^B is not enough for a proper uniqueness constraint. A date might be relevant here. Or is Course a homonym, both standing for a course with a unique ID in the (academic) program and also standing for a course in a particular academic year (where a course-date combination might be identifying)? And is *Enrollment* a unequivocal name for concept C? Clearly, the Engineering of the Functional Requirements (EFR) is not finished yet!

The counter-argument that the system already gives each object a *unique* object ID (in OO) or a *unique* database key (in a DBMS) fails of course, because that is not a user-based uniqueness property. In our example: how to distinguish two different enrolments of the same student for the same course? Moreover, this argument might simply ignore many or even all user-defined uniqueness constraints…

Another, subtle example of a potential mismatch is about indexes: A programmer might freely decide to add or delete indexes or even clustered indexes. This probably influences performance. However, adding or deleting a *unique* index not only influences the performance but also influences the 'semantics': it adds or deletes a uniqueness constraint. So, where adding or deleting indexes or clustered indexes seems a purely SE-concern, adding or deleting a *unique* index is not: it should be in line with the functional requirements.

5 In Conclusion

In this position paper, we presented our view on and approach to the development of the functional requirements of information systems. In our view, the main development line for the Engineering of *Functional* Requirements (EFR) should be:

EFR -> Conceptual Model -> SE

A main output of the EFR process is a conceptual model, to be used as a primary input to the Software Engineering (SE) process. EFR isn't just a part of SE. EFR and SE require rather different skills; see Fig. 6.

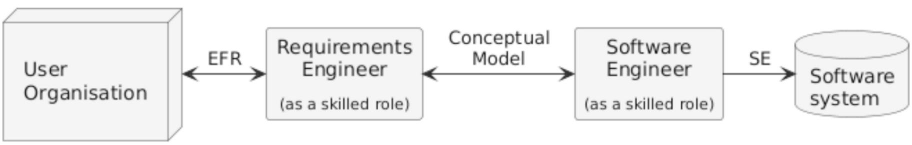


Fig. 6. The position of Requirements Engineer, Conceptual Model, and Software Engineer in Business Modeling and Software Design

Moreover, EFR should result in a *conceptual model* of the system to be built, and not just in a long list of Requirements Statements (e.g., of the form "The system shall …", "The system shall …", etc.)

A Conceptual Model must consist of a Conceptual *Data* Model (for the 'statics') and a Conceptual *Process* Model (for the 'dynamics'), to be developed concurrently and be aligned and consistent with each other. They are the two sides of the same coin!

$$\boxed{\mathrm{CM} \equiv \mathrm{C\underline{D}M} \oplus \mathrm{C\underline{P}M}}$$

Another take-away: Don't think only in terms of (isolated) development steps but also in terms of a complete development path (see Fig. 3 and Table 1). The development path includes different disciplines (e.g., understanding of the application domain at hand, requirements engineering, software engineering), which *interact* and have to be *integrated* to come to useful systems. Therefore, the topic is not just multi-disciplinary but in fact *inter*-disciplinary.

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Prompt Engineering for Analyzing Acceptance Criteria for Functional Requirements

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Abstract. This research evaluates the effectiveness of various LLM prompt engineering techniques in analyzing acceptance criteria in Gherkin for forming functional requirements in Rimay. Effective application of these techniques would assist the human-expert process of analyzing acceptance criteria to develop requirements. The prompt techniques we evaluate are few-shot learning, chain-of-thought and role-play, with each having either a low or high LLM temperature. Precision-recall metrics provide evaluations for each. The structured language Gherkin defines user stories in Agile software development for defining acceptance criteria. Rimay defines functional requirements in a standardized controlled natural language. The results show that the prompt technique few-shot learning with low LLM temperature gave the best results for translating from Gherkin to Rimay. The chain-of-thought technique combined with a high LLM temperature gave reasonable results. Role-play gave the least accurate results.

Keywords: Gherkin · Controlled Natural Language (CNL) · acceptance criteria · Agile environment · Rimay · functional requirements · prompt engineering · Few-shot learning · Chain-of-Thought · Role-Play

1 Introduction

The Agile software development approach has stakeholders create user stories with acceptance criteria (AC) that indicate story completion. The semi-structured natural language Gherkin [7] defines acceptance criteria. After the completion of a user story, the Agile process analyzes acceptance criteria to form functional requirements. The controlled natural language (CNL) Rimay captures functional requirements [11]. This research focuses on the translation of acceptance criteria in Gherkin into functional requirements in Rimay.

The acceptance criteria are written in Gherkin, a semi-structured text with the following structure: Given ... When ... Then. This structured text is in the order of precondition, an action or trigger and postcondition [7]. This format helps validate the delivered functionality with test cases written in a language

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that can be understood by software developers, testers and users alike. In this method, a functional requirement is formulated from a particular user perspective. Acceptance criteria are often used in collaboration with the customer, using clearly readable language. The main difference between acceptance criteria and functional requirements is that acceptance criteria indicate when a functionality is complete, whereas functional requirements indicate exactly what the product should do.

Finally, we use the CNL Rimay for the formulation of functional requirements [11]. Rimay helps reduce ambiguity in discussions with the software developers and the customer. It was developed specifically for functional requirements, focusing on developing IT systems [11].

This study applies Large Language Models (LLMs) in analyzing acceptance criteria in Gherkin to generate corresponding functional requirements in Rimay. We use a general-purpose LLM that is thus not specifically trained for Rimay or Gherkin, and thus relies on general knowledge, supplemented by the prompts. The research question of this paper is as follows: *How, when, and to what extent can LLM prompt engineering contribute to converting Gherkin acceptance criteria into Rimay functional requirements documentation?*

2 Related Work

Proposed LLM prompt techniques include chain-of-thought (CoT), few-shot learning (FSL) and role-play (RP) [9]. LLM settings include temperature, which influences the creativity of prompt responses. This research compares the use of these three prompt techniques along with varying LLM temperature.

Irfan [4] proposed tips that apply to LLM prompts in general, as well as specifically for the FSL, CoT and RP techniques. One tip is to start with simple prompts and then incrementally expand them. Another is to be accurate and include precise instructions in the prompts. They also suggest using clear delimiters to separate instructions from context. Their delimiter is the substring '###'. We apply Irfan's tips in our experiments.

Few-shot learning is training an LLM service with example input and output within a single chat with the LLM, instead of training that builds or extends an LLM. The initial prompts therefore give paired inputoutput examples. Our experiment's FSL prompts include examples of Rimay's output [11]. In this way, the LLM learns how Rimay is constructed so that it can then make its own conversion using the Gherkin information. Also included in the prompt is one example of Rimay output with the desired structure, as described in Dang's research [3].

While FSL trains by example, chain-of-thought prompts teach by explanation. The CoT technique uses a question-answer structure [6]. We apply this question-answer structure here to test whether components of Gherkin can translate directly to Rimay. The last question in the LLM prompt formulates the new situation of Gherkin in Rimay. This technique proposes the development of a persona executing a task [8]. Here, this would allow separate instructions simulating a conversation in which one person speaks Gherkin and the other person speaks Rimay. With this information, the LLM may be able to convert new Gherkin acceptance criteria inputs to Rimay.

Acceptance criteria in the software industry are written according to an established structure using the Gherkin format. O'Brien's research discusses this in more detail along with an explanation of the structure in which acceptance criteria are written [7]. In addition, a dataset is available for research that defines many acceptance criteria in the Gherkin format [1].

Veizaga's research proves that it is possible to use Rimay functional requirements as input and acceptance criteria as output [12]. These acceptance criteria are later used for writing software tests and documentation. The acceptance criteria in the study were also defined according to the Gherkin format. The tool Paska interprets text using Natural Language Processing (NLP) and tags the Rimay input requirement with Part-of-speech (POS) tagging [12]. The tool DSL-Rimay checks for syntactic correctness of Rimay and verifies that Rimay requirement are written according to a logical order and structure [11]. We apply both of these tools in this research.

In Veizaga's main description of Rimay [11], the minimum components needed for an official Rimay requirement are ACTOR, MODAL_VERB and SYSTEM_RESPONSE. Veizaga gives "shall" and "must" as the main examples of MODAL_VERB. Thus, our research applies at least the three minimum Rimay components, with "shall" and "must" as the possible modal verbs. We maintain a scope in this research on what each language requires and, for each required component, what the corresponding component in the other language is.

Gherkin defines what functionalities are required before a portion of the software application can be considered complete. The language can describe, from a user scenario, what steps are completed with what conditions. In contrast, Rimay can define much more from a technical point of view, with fixed events, conditions and even loops, exactly what happens in the desired software system. Rimay is much more elaborate in terms of grammar and can describe as precisely as possible which parts are important [11]. Whereas Rimay is a controlled natural language, Gherkin is structured natural language.

We model the overlap between Gherkin and Rimay by analyzing research on the ontology of Behavior-Driven Development [10] and Rimay [12]. Both Rimay and Gherkin have Actors. Rimay's WHILE_STRUCTURE overlaps with the precondition (Given) of Gherkin. The WHEN_STRUCTURE of Rimay corresponds with Gherkin's event trigger (When). Finally, Gherkin's postcondition (Then) overlaps with the SYSTEM_RESPONSE in Rimay. The relationship between Rimay and Gherkin is elaborated in Veizaga's research, which incidentally still uses an intermediate step for translation between the two structures [2].

For the study, a direct translation is performed from one acceptance criterion in Gherkin to one functional requirement in Rimay. The mandatory components, such as ACTOR and MODAL_VERB, combined with when and while are used as the expected Rimay output. Using the Paska tooling and DSL-Rimay (syntax checking), validation can then be performed on the generated Rimay by the LLM. A score will also be assigned to the generated Rimay based on a manual review. A definition of Rimay's structure can be found in Veizaga's research [11]. O'Brien's research [7] provides a clear explanation of Gherkin's structure. Gherkin's dataset [1] serves as sample input text and provides variations for analysis of LLM responses to different Gherkin scenarios.

3 Method

This research's goal is to compare how well various LLM prompt techniques generate Rimay from Gherkin. Our focus within Rimay is on four components that correlate well with Gherkin, three of which are required [12]. The following LLM prompt techniques are employed: few-shot learning (FSL), chain-of-thought (CoT) and role-play (RP). For each prompt technique, we apply two different temperature settings: low (0.2) and high (1.3). We perform thus six experiments: the three techniques, with each at both low and high temperatures.

In order to calculate precision and recall, we give prompts with Rimay that is both correct and incorrect for the given Gherkin input. Each prompt also informs the LLM whether the generated Rimay is correct or incorrect for the given Gherkin. This lets the LLM learn from both. It also enables precision-recall calculations because the correct Rimay gives position returns, and the incorrect Rimay gives negative returns. This provides the detection of true and false positives, and true and false negatives, needed for precision-recall calculation.

For the input, we apply each prompt the tips from Irfan [4] regarding delimited instructions, examples, and incrementally increasing prompt complexity. We use only the following Rimay components: WHILE_STRUCTURE, WHEN_STRUCTURE, ACTOR, MODAL_VERB and SYSTEM_RESPONSE. We avoid use of Gherkin's AND construct because it goes beyond the GIVEN/WHEN/THEN foundation of Gherkin, making processing more complex. The actors were predetermined and defined in Rimay for each text.

For the output, we evaluate each Rimay requirement generated with three techniques: Paska to assess valid Rimay content, DSL-Rimay to assess correct syntax and a manual review to assess content translation. Paska evaluates the generated Rimay requirements substantively by checking for several textual components. DSL-Rimay evaluates the syntax. Each of our evaluations with Paska and DSL-Rimay gives a score. Our manual analysis assigns one of the following assessments per generated requirement: Unsatisfactory, Moderate, Satisfactory and Good. This is an iterative process that involves constant evaluation and analysis of which formulation of LLM prompt technique works best. The entire implementation is developed in a virtual machine and all required source code is in a repository on Github[1].

For calculating each precision-recall score, Table 1 shows the different base scores from which we calculate the total accuracy We calculate each score from the results of all three evaluation techniques: Paska content checks, DSL-Rimay syntax checks and our manual review. Paska and DSL-Rimay give a negative

[1] https://github.com/koenieee/LLPTE.

Table 1. The calculation for assessing each Rimay requirement generated.

Paska		DSL-Rimay		Manual	
Error	Adj.	Error	Adj.	Category	Adj.
Incomplete requirement	–25%	EDF	–10%	Insufficient	–10%
Not requirement	–20%	RULE_STRING	–7%	Moderate	–5%
Incomplete system response	–15%	Missing	–5%	Sufficient	+10%
Coordination ambiguity	–10%	other errors	–1%	Good	+15%
Incomplete condition	–10%	**Total score =**			
Non-atomic requirement	–5%	((100 - sum Paska adjustments)			
Incorrect order requirement	–5%	- (100 - sum DSL-Rimay adjustments))			
Passive voice	–5%	/ 2			
Not precise verb	–5%	+ sum manual adjustments			

adjustment for each error found. Our manual assessments adjust both negatively and positively The total score is the average of the sums from our Paska and DSL-Rimay adjustments, plus an adjustment from the manual score. From all the precision-recall values for each experiment, we calculate the average of the scores for all generated requirements.

4 Results

The study compares the prompt techniques few-shot learning (FSL), chain-of-thought (CoT) and role-play (RP) for analyzing Gherkin acceptance criteria into Rimay functional requirements. For Rimay validation, Paska and DSL-Rimay [12] are used. In addition, a score is also manually assigned to the generated Rimay output. Rimay validation requires predefining the actors that align with the dataset mentioned in Sect. 3. An important factor for consistency of responses is the LLM temperature setting. This LLM temperature causes the LLM to answer more creatively. A number between 0 and 0.5 is recommended for translations or transformations, while a number higher than 0.5 is more suitable for generating creative texts. This is due to the randomness of the texts the LLM generates, as described in Sect. 2.

In this study, two LLM temperature values are used for each experiment (FSL, CoT and RP). The LLM temperature chosen is 0.2 and 1.3 for all three LLM prompt techniques. The Gherkin input dataset for all experiments consists of 19 Gherkin acceptance criteria. The dataset was additionally prepared manually This includes ensuring consistent use of the same actor. For each experiment, the LLM prompt used is different. For all experiments, the text "### Input Data" appears for each different Gherkin input acceptance criteria. What is especially important here is that the WHILE, WHEN then/must structure used has a logical order. The prompts are available on this paper's GitHub repository.

4.1 Experiment Few-Shot Learning (FSL)

The first experiment evaluates the few-shot learning technique. The prompts here explain the language Rimay and what rules apply to it. Our FSL prompts contained quite specific instructions and examples, as proposed by Irfan [4], for translating from Gherkin to Rimay. The global sequence of Rimay with the appropriate WHILE, WHEN structures and actors is further explained for the LLM with precise instructions. Prompts include explicitly incorrect Rimay output, with incorrect order or definitions.

Figure 1 shows similar accuracies for both low LLM temperature and high LLM temperature. This experiment gives good results: accuracy is 92% for both low and high temperatures. The use of specific instructions and examples seems to have contributed the similar scores at both temperatures. The translation from Gherkin to Rimay reasonably matches the expected structure. Some generated outputs did not follow the correct Rimay structure, although they did include the minimum requirements. Prompts with incorrect order lead more often to errors in Rimay definitions.

4.2 Experiment Chain-of-Thought (CoT)

The second experiment uses the chain-of-thought technique. In this experiment, the LLM is given several examples of successful translations from Gherkin to Rimay. The CoT LLM prompt contains 3 examples of correct Gherkin to Rimay translations. These translations, provided as examples, are self-written and follow the structure defined in Sect. 2, exhibiting similarities with Gherkin and Rimay. The examples are not exactly the same as the Gherkin input data, as this would bias the results. This prompt technique does not include background information on how the CNL is defined, as few-shot learning does. The LLM prompt used here contains examples of translations of Gherkin and Rimay that are intentionally incorrect. The overlapping defined Rimay structure is defined in the wrong order, or mandatory parts of Rimay are missing from the translation.

Figure 1 shows the results of the LLM prompt technique chain-of-thought. For FN and FP, chain-of-thought sometimes generated exactly the same Rimay structure as the input Gherkin acceptance criteria. The only thing translated were some Rimay components, written in the present tense by the LLM. In addition, some Rimay components were sometimes missing. These results were less accurate (accuracy of 65%) than with few-shot learning (accuracy of 92%). For chain-of-thought, a higher LLM temperature seems to perform better compared to a lower LLM temperature.

4.3 Experiment Role-Play (RP)

This experiment about role-play uses a positive prompt that imitates a conversation in which two people discuss translating Gherkin to Rimay. This conversation uses individual components of Gherkin to indicate the way in which the final translation should take place. The LLM plays the role of the person generating

Rimay. Compared to few-shot learning, no background information on Rimay is given in this technique. Compared to chain-of-thought, there is no overarching example in which all WHILE, WHEN and THEN/MUST structures are mentioned. However, information on how to structure the Rimay requirement is given at the end. For the negative prompt, the same conversation is formulated. The only difference is that now the translation from Gherkin to Rimay is explicitly misnamed within the conversation of these two individuals.

As shown in Fig. 1, the role-play LLM prompt technique was the poorest performer. The overall structure was often not followed. For example, the WHILE structure was often confused with the WHEN structure. The higher temperature leads to mimicking the LLM role-play conversation instead of generating Rimay. In addition, the overall structure of Rimay was sometimes missed when generating the functional requirement. A lower temperature gave slightly better results (accuracy of 68%) with role-play.

4.4 Comparison of Experiments

Figure 1 shows a total summary of all results of the three techniques. The recall of few-shot learning is relatively high (100% and 94%). Whereas for role-play and chain-of-thought, a relatively lower score was obtained. Few-shot learning also scored high for accuracy. What stands out is that precision for role-play received a relatively high score of 94%.

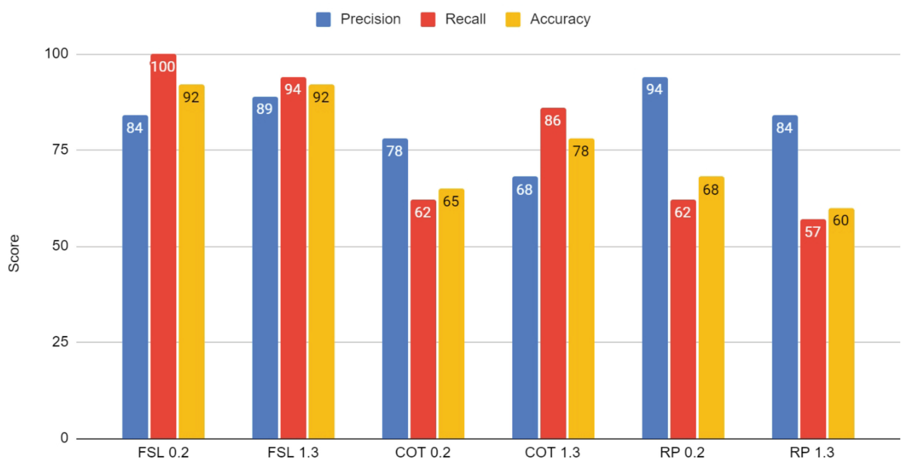

Fig. 1. Precision-recall of LLM prompt techniques.

As shown in Fig. 1, few-shot learning with a temperature of 0.2 scored the best (92%). On the other hand, the score of FSL with a high LLM temperature of 1.3 makes little difference (91%). In addition, chain-of-thought (68%, temperature 0.2) and role-play (67%, temperature 1.3) technique score about the same. However, the chain-of-thought technique does achieve better accuracy (77%, Fig. 1) with high LLM temperature. Role-play performs less well on average with high LLM temperature (67%), but again achieves higher accuracy than chain-of-thought with high temperature (Fig. 1). The role-play technique performed worst with high LLM temperature. Notably, the LLM struggled here to understand the role-play call properly.

Some Gherkin acceptance criteria translated better into Rimay requirements due to varying acceptance criteria complexity. Short and simple Gherkin acceptance criteria translated more accurately than longer and complex ones. The syntax check scored differently for each generated Rimay requirement. This is mainly because of the word choice used (Rimay components), CNL order and content words that do not quite match the known Rimay components. The role-play technique generated few syntax errors. This is because the Rimay requirement was generated on multiple lines, so only the EOF (End-Of-File) error was present. This error was handled with a higher negative score in the scoring system as defined in Sect. 3.

5 Discussion

Paska encountered difficulties when processing text that contained no Rimay text at all, resulting in no score being assigned in such cases. On rare occasions, the LLM produced incorrect outputs, leading to missing Rimay text. A check for correct syntax required the definition of Rimay actors. Our prompts sometimes generated Rimay actors incorrectly, leading to syntax errors and thus requiring a syntax check after generation. Moreover, the use in Gherkin of complicated words and sentence structures and longer Gherkin input text generated different Rimay components and therefore produced varying results. It is more important that the overall Rimay structure match expectations rather than syntactic correctness.

One limitation was the absence of a Rimay dataset for comparison material. Therefore, we formulated the Rimay dataset used for comparison ourselves. Because Rimay is a large CNL with about 61 components [11], there are multiple ways to formulate a Rimay requirement. With the definition of several synonyms, Rimay consists of 200 components. This complicates the definitive assessment of correctness. Furthermore, the style in which a Rimay requirement is formulated depends on the evaluator's own interpretation. Here, the evaluator of the generated Rimay requirement is biased.

The scoring system compared the results of the LLM prompt techniques, thus focusing to a lesser extent on the correctness of Rimay. A potential drawback is that both the syntax verification software (DSL-Rimay) and the Rimay content verification software (Paska) are based on the work of the same authors. The variation with LLM temperature showed little difference concerning LLM prompt techniques. The role-play technique [8] scored worse at a high temperature than at a low LLM temperature.

The role-play technique had fewer specific instructions as it relies mainly on examples of a translation conversation from Gherkin to Rimay. We applied

Shanahan's role-play technique [8], which is formulated as a conversation between two people. Here, one speaks Gherkin and the other Rimay. The results for role-play are somewhat lower than for FSL or CoT. In the same study [8], role-play does not always appear suitable for using 'hard facts'. The role-play technique seems less well suited for translating Gherkin to Rimay CNL.

Chain-of-thought scores better at a higher LLM temperature. One possible explanation is the difference in the formulated LLM prompt. As described in Lee's literature, chain-of-thought clearly followed the guidance of instructions and examples [6]. This was also consistent with the results generated in Sect. 4. The more creatively worded the prompt was, the more the LLM generated words that do not exist as components in Rimay.

6 Conclusion

The best results were obtained with few-shot learning and a low LLM temperature. The LLM prompt technique chain-of-thought also yielded good results, though in combination with a high LLM temperature. Finally, the role-play LLM prompt technique was the least successful. RP is better suited for creative situations. The more simply and specifically a prompt is formulated, the better an LLM is able to deliver the desired end result.

The approach of using few-shot learning with examples provides a global structure of Rimay in the correct order that can serve as a good starting point for correct requirements. The Rimay generated by the LLM contains errors but still has some correct information that is useful for further perform differently for the other Rimay components. Further post-generation human work may therefore be required to add Rimay features that are less well supported, as well as cleaning up what the LLMs generate. Although LLMs can provide good recommendations, human verification of these results is still necessary to ensure accuracy.

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Towards Self-adaptive Information Systems with Federated Learning and Decentralized Optimization

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Abstract. The increasing complexity of modern information systems necessitates adaptive frameworks capable of dynamic learning and real-time optimization. Traditional centralized architectures often struggle with scalability, security, and evolving computational demands, leading to inefficiencies in data-driven decision-making. In response, self-adaptive information systems have emerged as transformation approach, leveraging artificial intelligence (AI), federated learning, and decentralized optimization methods to enhance adaptability, efficiency, and security.

This research explores the integration of self-adaptive systems with federated learning to improve decision-making while maintaining data privacy and security. Federated learning enables decentralized data processing across multiple nodes, ensuring privacy preservation without centralizing sensitive user information. Additionally, decentralized optimization techniques enhance the robustness and efficiency of system learning by distributing computational workloads and minimizing bottlenecks in large-scale environments.

To validate these methodologies, we test federated learning and decentralized optimization on financial dataset containing attributes such as credit limits, demographic factors, payment history, and default risks. By training AI models on distributed nodes while optimizing learning rates and resource allocation, we aim to improve predictive accuracy in financial risk assessment while reducing computational overhead.

Experimental results indicate that self-adaptive learning models outperform conventional centralized approaches, offering greater resilience in fluctuating data environments. The findings underscore the potential of self-adaptive information systems to enhance predictive capabilities, optimize resource allocation, and ensure secure financial data processing. This study provides foundation for further advancements in adaptive AI-driven financial systems, ensuring scalable, privacy-conscious, and efficient decision-making frameworks.

Keywords: Self-adaptive information systems · Federating learning · Decentralized Optimization

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1 Introduction

In an era of rapid digital transformation, the need for intelligent, self-adaptive information systems has grown exponentially across various domains, including finance, cybersecurity, and cloud computing. Traditional centralized systems often struggle to scale effectively, maintain privacy, and respond dynamically to evolving operational challenges. Self-adaptive information systems address these limitations by leveraging artificial intelligence (AI), machine learning (ML), and optimization techniques to autonomously adjust system behavior in real time, enhancing adaptability and efficiency.

Federated learning has emerged as a crucial approach in self-adaptive systems, allowing decentralized data processing while preserving privacy. Unlike conventional ML models that rely on central data aggregation, federated learning enables distributed nodes to train models independently, sharing only essential learning parameters. Data heterogeneity, communication overhead, and slow model convergence present obstacles to deploying scalable self-adaptive financial systems. Additionally, conventional fraud detection methods struggle with imbalanced datasets, where fraudulent cases are vastly outnumbered by legitimate transactions, impacting predictive accuracy.

Similarly, decentralized optimization offers a promising framework for resource-efficient computation, but its integration within self-adaptive systems poses challenges related to model consistency, adaptive learning strategies, and real-time decision execution. Without effective optimization mechanisms, federated learning models may fail to deliver high-accuracy fraud detection and financial risk assessment in real-time.

The aim of the research work is to evaluate the effectiveness of federated learning (FL) and decentralized optimization (DO) in financial risk assessment. It utilizes a dataset containing key attributes such as credit limits, payment history, billing amounts, and default probabilities. The structured dataset facilitates the identification of default risk patterns, providing valuable predictive insights into financial behavior. By implementing AI-driven models across distributed nodes, the research seeks to enhance predictive accuracy while ensuring data privacy and optimizing computational efficiency.

Through this investigation, we explore the intersection of self-adaptive systems, FL, and DO to understand their impact on financial decision-making. Our findings contribute to the ongoing evolution of adaptive intelligent systems, paving the way for privacy-conscious, scalable, and high-performance solutions in the future of financial technology and automated decision-making systems.

2 Review of Literature

The advancement of self-adaptive information systems has led to significant transformations in AI, FL, and DO. These methodologies collectively empower systems to autonomously adjust their behavior, optimize workflows, and improve efficiency while ensuring scalability, security, and adaptability.

The study by [1] introduced Non-Overlapped Risk-Based Bagging Ensemble (NRBE) model for credit card fraud detection, demonstrating enhanced recall by 50% and cost reductions compared to existing models such as AIRS and CSNN. The research leveraged transaction attributes, including amount, time, location, transaction type (online/offline), and behavioral spending patterns, to improve fraud detection efficiency.

DO plays a crucial role in self-adaptive systems by facilitating resource distribution across interconnected nodes, reducing computational bottlenecks, and enhancing AI-driven fraud detection models. Optimization algorithms allow dynamic system tuning, ensuring fraud detection models evolve in real-time to counter emerging financial threats.

The research paper [2] proposes an innovative methodology to optimize dataset size for AI models while maintaining accuracy and coverage. The hybrid approach addresses scalability and data quality challenges in AI/ML pipelines [2]. The potential for self-learning AI systems to autonomously adjust optimization strategies reinforces the flexibility and robustness of decentralized information systems.

The authors [3] suggested frameworks and methodologies for modeling business processes in self-adaptive systems, enabling these systems to autonomously evolve and adapt their behavior at runtime, while maintaining alignment with business goals and operational requirements.

BPM for self-adaptive systems [3] represented a paradigm shift from static, human-driven change management to dynamic, autonomous adaptation. The research underscored the need for new abstractions, modeling tools, and architectural patterns to fully realize the potential of self-adaptive business process management.

The research [4] introduced a framework for modeling the behavior of mobile agent groups working toward a shared objective. The study demonstrated multi-agent coordination, which could be enhanced through FL, enabling decentralized training without relying on a centralized dataset.

In research [5] implemented several techniques, including designing an anomaly detection architecture based on Business Process Modeling Notation (BPMN). The current system designed anomaly detection architecture, but implementing FL would enable distributed fraud detection without centralizing sensitive data.

The research study [6] investigated the application of machine intelligence systems to automate software testing. DO models could help dynamically allocate testing resources, improving real-time performance while minimizing computational overhead.

In [7] author developed a web-based framework model tailored for financial organization and proposed structured logical architecture for the payment system. The logical architecture proposed for the payment system can be refined through DO, ensuring efficient resource allocation across multiple nodes.

The authors [8] observed review and advance methodologies for integrating adaptive capabilities into business process models, enabling systems to autonomously monitor, analyze, plan, and execute changes in response to environmental or internal shifts. The study determined CSFs affecting BPR, which can be improved through decentralized optimization strategies. Decentralized algorithms refine process workflows dynamically, ensuring enhanced responsiveness without over-reliance on a central governing system.

The authors [9] developed an intelligent, self-adaptive decision-making model integrated with business process model that supports autonomous, real-time adaptation of product innovation in manufacturing and engineering. The study highlighted flexibility and responsiveness, which align with decentralized optimization strategies that can improve computation models and manufacturing process adaptability.

The paper [10] established key requirements and constraints necessary for constructing well-organized and manageable capabilities and capability maps. The paper described efficient business object transitions, which could be improved through decentralized optimization algorithms. Optimized workflow refinement ensures dynamic allocation of resources, allowing self-adaptive enterprise systems to autonomously evolve in response to changing operational demands.

The authors [11] established a mapping from UTIL, a universal textual instruction language template with formal and declarative semantics, to both activity diagrams and BPMN. Implementing optimization algorithms could improve real-time process validation, enabling adaptive decision-making across dynamic operational environments.

The paper [12] introduced solution to the problem by designing a software system that utilizes OpenAI's ChatGPT to extract contextual details from BPMN diagrams and created corresponding UML class diagrams. The proposed approach leverages AI automation, but integrating federated learning allows multiple organizations to collaboratively refine AI-driven process modeling without sharing sensitive business data.

The paper [13] explored the relationship between context awareness and external influences, emphasizing the importance of incorporating public values, regulations, and norms into the design of context-aware software systems. By incorporating context-awareness into self-adaptive FL frameworks, intelligent systems can evolve into decentralized, regulation-conscious decision platforms, strengthening AI resilience in financial organizations.

3 Main Part

In the financial sector, the integration of Business Process Modeling (BPM) within self-adaptive systems has brought about transformation shift in how institutions address critical functions such as fraud detection, portfolio management, and regulatory compliance. Financial services operate in a highly dynamic and interconnected environment, where new risks and regulatory demands emerge continually. Self-adaptive systems, when paired with BPM methodologies, enable financial organizations to stay ahead of these challenges by introducing an unparalleled level of automation, adaptability, and precision.

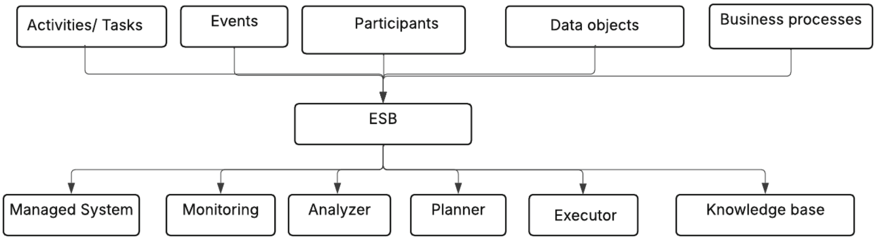

Fig. 1. Self-adaptive business models in financial organization.

According to Fig. 1 the elements: Activities/Tasks, Events, Participants, Data Objects, and Business Processes represent the core components of a business process model in financial organization. They define: what work is done (activities/tasks), when it occurs or is triggered (events), who does the work (participants), what information is used or generated (data objects) and how everything is organized into end-to-end flows (business processes). These BPM elements define the logical structure and operational needs of the system. ESB acts as the integration layer, connecting business process components to the self-adaptive infrastructure. It handles communication, transformation, and routing between loosely coupled components. In self-adaptive systems, flexibility and dynamic reconfiguration are essential. ESB enables runtime adaptability by managing interactions between different modules. Self-Adaptive system components consist of: Managed system present a system being controlled, executing the business processes. Monitoring collects data from BPM elements and the system's operational environment. Analyzer evaluates runtime behavior against goals (e.g., performance, compliance) using monitored data. Planner decides on corrective or optimizing actions when deviations are detected. Executor carries out the adaptation actions (e.g., scaling resources, modifying workflows). Knowledge Base stores domain knowledge, historical data, and system state information to support decisions.

This architecture supports the bridging BPM and SAS, which influence to mapping business modeling concepts to adaptive control structures. Centralized orchestration via ESB allows seamless flow of control and data, making the system agile and responsive to internal or external changes.

Federated learning (FL) addresses these limitations by allowing decentralized nodes to collaboratively train models while preserving local data privacy. However, ensuring adaptive optimization within FL frameworks remains a challenge due to imbalanced data distributions, convergence inconsistencies, and dynamic system constraints. Decentralized optimization complements FL by refining learning strategies, adjusting computational loads autonomously, and facilitating efficient coordination across distributed environments.

This research implements a self-adaptive federated learning framework with decentralized optimization in credit risk assessment, leveraging the Default of

Credit Card Clients dataset to evaluate adaptive learning mechanisms, model convergence, and performance improvements.

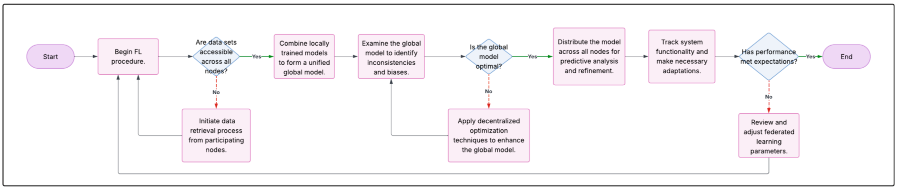

Fig. 2. Flowchart of Federated Learning.

The Fig. 2 illustrates the process of decentralized model training across multiple nodes while preserving data privacy. The diagram outlines key stages in the workflow, highlighting how individual devices contribute to a shared global model without centralizing raw data.

In data distribution across nodes each node (device or server) maintains its own dataset locally. Each node trains local model using its private dataset. Models learn patterns from the data without exposing it to external servers. The locally trained models send only model parameters to central server. The aggregation process combines these parameters to form global model. The decentralized optimization method refines the global model using feedback from participating nodes. Adjustments ensure improved performance across diverse datasets while maintaining security. Once model refined, the global model is redistributed to all nodes. The system continuously updates itself, adapting to new data patterns.

FL ensures data confidentiality by keeping local datasets decentralized. The system allows distributed model updates, making it robust for applications in FinTech. By aggregating model parameters instead of raw data, federated learning reduces communication overhead while optimizing learning processes.

4 Experiment

The 'Default of Credit Card Clients' dataset [14], a benchmark dataset for credit risk modeling, serves as the primary data source for evaluating federated learning performance. The dataset contains customer demographics, payment history, credit limits, and transaction records, making it ideal for self-adaptive anomaly detection.

Table 1 outlines the key attributes of the dataset, ranging from credit balances, repayment history, and default predictions. The experimentation process is conducted using Jupyter Notebook with Python, employing Logistic Regression (LR) models trained across decentralized nodes via FL [15].

Table 1. Dataset description of Credit card clients.

Attribute	Description
ID	Identification number
LIMIT_BAL	Amount of given credit (NT dollar)
SEX	Gender (1 = male; 2 = female)
EDUCATION N	Education level (1 = graduate school, 2 = university, etc.)
MARRIAGE	Marital status (1 = married, 2 = single, etc.)
AGE	Age in years
PAY_0, PAY_2, ..., PAY_6	Past payment history for six months or repayment status in months 0–6
BILL_AMT1 to BILL_AMT6	Bill statement amounts
PAY_AMT1 to PAY_AMT6	Previous payments
default.payment.next.month	Default label, Binary (1 = defaulted, 0 = not defaulted)

The system successfully executed three federated learning rounds, indicating a decentralized optimization process where multiple local models (from different nodes/clients) contributed to improving the global model. The gradual completion of rounds suggests that the system is capable of autonomously coordinating model updates without centralized control, a key feature of self-adaptive systems. The FL framework is simulated using decentralized clients, each operating on a local subset of the dataset. The FedAvg aggregation algorithm is used to synchronize client models through federated rounds, simulating an adaptive decentralized learning mechanism. The system successfully executed three federated learning rounds, demonstrating the feasibility of adaptive coordination across distributed nodes. FL ensures decentralized optimization, wherein local models refine their predictions without requiring data centralization. The results indicate that FL enhances privacy-preserving AI workflows while facilitating scalable model convergence.

The classification report results highlight high precision for majority class (Class 0), achieving: Precision = 0.82, Recall = 0.97, F1-score = 0.89. Conversely, the model exhibits lower performance for the minority class (Class 1), recording: Precision = 0.72, Recall = 0.24, F1 = 0.36. This imbalance poses challenges for self-adaptive federated learning, where certain nodes lack sufficient minority class samples, leading to model underfitting in risk-sensitive classifications.

The overall accuracy by LR 81% is good, but misleading due to imbalance. Macro F1 0.62 reveals weakness in handling both classes equally. The results demonstrate that while FL enables decentralized model training, class imbalance remains a challenge in self-adaptive systems. Future enhancements should focus on adaptive aggregation mechanisms and dynamic client-weighting strategies to improve minority-class performance without sacrificing global model robustness.

Stagnant metrics across rounds calculates Accuracy (0.8070) and Log Loss (0.4721) remain identical for all 10 rounds. The federated averaging (FedAvg) algorithm reached a fixed point where local client updates no longer change the global model. If all clients have very similar data distributions, their local models may converge to identical parameters. Log loss interpretation of 0.4721 (for binary classification) suggests moderate confidence in predictions, but no improvement over rounds.

On Decentralized optimization simulation splits data across 5 clients to simulate a decentralized environment (no central server). Each client operates on local subset, preserving privacy, core tenet of FL. Self-adaptation dynamically adjust number of clients based on system load or data drift. Clients communicate only with direct neighbors (decentralized coordination). Each client performs local SGD and averages parameters with neighbors. On Decentralized optimization knowledge diffuses through the network. Self-adaptation adjusts lr (learning rate) per client based on local loss. The experiment provides baseline decentralized FL implementation with ring topology, directly addressing on self-adaptive, decentralized systems. Key extensions for deeper alignment include: topology adaptation based on performance, personalized client models and automated hyperparameter tuning.

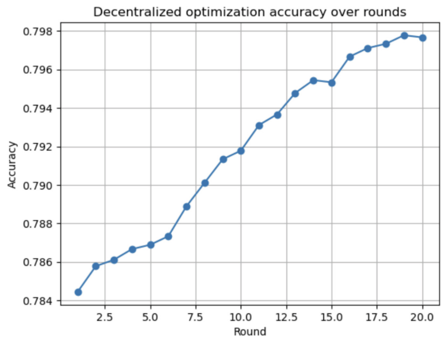

Fig. 3. Decentralized optimization accuracy over rounds.

Figure 3 illustrates accuracy progression across 20 training rounds, reinforcing that adaptive FL models maintain stable performance in decentralized environments. To counteract data imbalance challenges, adaptive aggregation mechanisms can be introduced. Strategies such as weighted aggregation, dynamic client selection, and self-regulating learning rates enhance the representation of minority classes in federated learning models.

5 Conclusion

The increasing complexity of modern digital environments demands intelligent, self-adaptive information systems capable of autonomous evolution, efficient resource distribution, and secure decision-making. Traditional centralized architectures pose significant challenges in scalability, data privacy, and dynamic optimization, necessitating a shift toward FL and decentralized optimization as foundational methodologies for adaptive AI-driven systems.

This research successfully demonstrated the integration of FL with decentralized optimization, showcasing their combined ability to preserve data privacy, enhance real-time model refinement, and optimize system-wide scalability. Using the 'Default of Credit Card Clients dataset', FL enabled distributed training of financial risk assessment models, while decentralized optimization ensured autonomous coordination of system adaptations without relying on centralized control. The overall accuracy by LR 81% is good, F1 score is 0.62 reveals weakness in handling both classes equally.

Key findings from this study highlight: FL enhances decentralized data security, eliminating the need for raw data exchange while enabling collaborative model improvements. Decentralized optimization refines adaptive learning frameworks, dynamically adjusting computational resources for optimized fraud detection and risk modeling. Self-adaptive federated systems require specialized aggregation techniques, particularly to mitigate class imbalance challenges in imbalanced datasets.

The study further underscores the necessity of weighted aggregation mechanisms, adaptive client selection strategies, and automated hyperparameter tuning, ensuring federated systems dynamically evolve in response to shifting data distributions.

Future work should focus on: personalized FL models, tailoring adaptive AI techniques to individual client characteristics. Autonomous feedback-driven refinement, ensuring federated models self-adapt in real time for enhanced accuracy and resilience.

By integrating FL and decentralized optimization, self-adaptive information systems can revolutionize AI-driven financial decision-making, cybersecurity frameworks, and large-scale intelligent automation. This research contributes to advancing privacy-conscious, scalable, and adaptive information systems, reinforcing the viability of AI-driven autonomous intelligence for next-generation applications.

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Towards Generic Context Awareness Building Blocks that are Domain-Specific

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Abstract. A characteristic feature of adaptive systems is their ability to be context-aware which means being able to sense changes and adjust behavior accordingly. In developing such systems, engineers would often assume at design time several situation types that are of high occurrence probability and specify again at design time corresponding system behavior types. What about other situations? In most cases, any other situation would be addressed by a (standardized) fallback behavior. Still, this goes away from context awareness because such a behavior is not aligned to the "current" situation. As noted in previous works, a mitigation in this regard would have been the provision of real-time algorithmic support and this is nevertheless insufficiently explored. Why? Because often there are too many possible-to-occur situations (besides the ones considered at design time) that constructing an algorithm would become challenging. In this regard we see solution directions in the perspective of Data Analytics, inspired by the developments in recent years and referring to previous work addressing Bayesian Modeling. The idea is that: (i) Under a fallback behavior we classify and/or cluster the "current" situation such that we establish where it "belongs" to; (ii) We then statistically derive a match between the established "situation space" and a corresponding "desired behavior space". That is how the fallback behavior would be much more specific to the situation at hand, this leading to a more effective context-aware system. We present those ideas in the current position paper, planning more elaboration and then validations as future work.

Keyword: Context awareness; Fallback behavior; Data analytics

1 Introduction

A characteristic feature of adaptive systems is their ability to be context-aware which means being able to sense changes and adjust behavior accordingly, as studied in previous work [1–5].

In developing such systems, at design time, engineers would often assume several situation types that are of high occurrence probability and specify corresponding system behavior types. This often concerns context indicators that help sensing a contextual

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change [4], for example: a monitored person has moved from Location A to Location B, or another example: a monitored person is no longer with normal blood pressure, and so on. Further, even though most often establishing the context situation and/or contextual changes is done counting on sensors, there may be also other ways – counting on predictions, for example [3]. Anyway, all this only concerns situations foreseen at design time.

What about other situations? In most cases, any other situation would be addressed by a (standardized) fallback behavior [4]. Still, this goes away from context awareness because such a behavior is not aligned to the "current" situation.

As noted in previous works, a mitigation in this regard would have been the provision of real-time algorithmic support and this is nevertheless insufficiently explored, and is considered **challenging** [6].

Why? Because often there are *too many possible-to-occur situations* (besides the ones considered at design time) that constructing an algorithm would be far from easy.

In this regard we see *solution directions* in the perspective of **Data Analytics** [7], inspired by the developments in recent years and referring to previous work addressing particularly *Bayesian Modeling* [4, 6]. The idea is that:

- Under a fallback behavior we classify and/or cluster the "current" situation such that we establish where it "belongs" to.
- We then statistically derive a match between the established "situation space" and a corresponding "desired behavior space".

That is how the fallback behavior would be much more specific to the situation at hand, this leading to a more effective context-aware system.

We present those ideas in the current position paper, planning more elaboration and then validations as future work.

The remainder of the paper is organized as follows: In Sect. 2, we provide background (state-of-the-art) information. In Sect. 3, we introduce an illustrative example that will be helpful in our elaborating further the abovementioned solution directions – they in turn are presented in Sect. 4. Finally, we conclude the paper in Sect. 5 where we also outline plans for future research.

2 State-of-the-Art

Still in 1980s-1990s, visionary researchers, such as Mark Weiser, had shared view on "ubiquity" concerning IT services delivered to users, expecting "for the future" that IT systems would be capable of "sensing" the situation of the user [8]. We consider Weiser the one who has firstly CONCEPTUALIZED the idea of CONTEXT AWARENESS. Those conceptualizations have been further developed by researchers, such as Dey [9] but only the advances concerning enabling technology (including telecommunications/networking, sensors, and minituarization of devices) have given "green light" to full value INDUSTRIAL EXPERIENCES related to context awareness, such as the AWARENESS project of 2005 [10]. It was twenty years ago today and one would expect huge developments after the mentioned project. Nevertheless, the bottom-up (technology-driven) approach pushed forward by Industry, has insufficiently inspired scientists and researchers to develop further the works of Weiser and Dey. We argue that knowledge is still scarce on how to adequately reflect business/user requirements in the design of effective context-aware (software) systems, and we argue that the current technology-driven context awareness approach leads to only partial fulfilment of domain needs and user needs. Efforts to contribute filling in that gap can be seen from our previous work delivering a conceptual proposal that concerns the goal of maximizing the user-perceived effectiveness, by means of context-aware software systems [5], extending this also to external factors [1]. Anyway, anything done, starting from Weiser and reaching 2025, essentially assumes (in our view) DESIGN TIME PREPARATIONS in the sense that: (i) We "decide" at design time which are the context situations the system-to-be would be "facing"; (ii) And also – which are the corresponding desired behaviors the system should deliver. We claim that this is partially due to the consideration of SENSOR TECHNOLOGY as essentially underlying with regard to context awareness [11] and sensors can be utilized and deployed only under pre-defined rules and considerations. In our previous work, we have tried to go beyond sensors and consider also PREDICTIONS as instrumental with regard to situation capturing [4, 6]; inspirational in this regard are considered the current data-analytics-related developments and related hardware advances that allow one to easily gather training data for the sake of classifying a "new" item, making *predictions* in this way, for example: "It is more likely that Alice, who is now entering the store, would buy a computer (and it is less likely that Alice would not buy a computer)". This is indeed somehow restrictive because such "predictions" are aligned to Statistics, which means that a Hypothesis and its alternative are to be considered [12]. But even with considering predictions, they are again directed mainly to situation types foreseen at design time. We hence argue that FALLBACK BEHAVIORS (see above) remain insufficiently explored and most current context-aware (software) systems essentially count on things foreseen at design time.

3 A Context-Aware Coach System

Imagine tech-facilitated coaches covering a vast network of national/international routes and aiming at providing maximum comfort to passengers not only during a trip but also while the coach is not moving, for example waiting at a station for a next departure. Such a coach runs a context-aware IT system whose role is to maximize the user-perceived effectiveness, and the "users" are the passengers. Further, two particular context situations have been considered in this regard, at design time, namely: SITUATION 1 (S1) – THE COACH IS IN A TRIP (between Station A and Station B) and SITUATION 2 (S2) – THE COACH IS NOT MOVING (waiting at Station A). Finally, sensors placed in the engine box of the coach can clearly indicate when the coach is moving (S1) and when the coach is not moving (S2).

Then: (i) Upon a transition from S2 to S1, the in-doors ventilation would be turned on, the passenger-belt indicators would be turned on (such that beeps are heard if a passenger has not put his or her seat belt properly), the WCs would be open, and so on; (ii) Upon a transition from S1 to S2, the in-doors ventilation would be turned off, the passenger-belt indicators would be turned off, the WCs would be closed, the in-door info screens (showing "currently" possible coach connections from the "current" station) would be turned on, and so on. Hence, all this is nothing new in the sense that there are many context-aware systems, "acting" like this, counting on design-time preparations, as already discussed.

What would happen nevertheless in the event of emergency (imagine that fire is noticed on board) – let's label this "SITUATION 3 (S3)"? In this example, there are no "design-time preparations" concerning S3. Still, we ASSUME that even though there are no "design-time preparations", some situations have at least been FORESEEN at design time, such as the emergency situation, and indication for this can be ALARM NOTIFICATION, triggered by any of the emergency buttons on board, that can be pressed by the coach driver and/or a passenger.

Hence, what could happen with regard to the coach is three-fold:

- A situation may occur, for which there are design-time preparations (in this case – S1 or S2);
- A situation may occur, for which there are no design-time preparations but the situations has been foreseen at design time (in this case – S3);
- A situation may occur that has not even been foreseen at design time (imagine that the coach is intercepted by a criminal gang).

As stated above, considering the situations for which there are design-time preparations, is not challenging; that's why we are only addressing the fallback-behavior cases. From them, we do not consider situations that have not even been considered at design time because of excessive complexity. Thus, in the remainder of the current paper, we ONLY consider SITUATIONS THAT HAVE BEEN FORESEEN AT DESIGN TIME even though for them there are no design-time preparations.

4 Towards Context Awareness Building Blocks – A Proposal

As already mentioned, in the current section, we elaborate the proposed solution directions presented at the end of the Introduction and supported by the above-presented illustrative example. We will firstly present the building-block way of modeling, secondly – we will consider the context awareness implications, and thirdly (on that basis) – we will introduce our proposed solution directions, by presenting a suggested architecture, supported by the example.

4.1 Business Engineering Building Blocks

In previous work from twenty years ago today, we have considered re-usable, replaceable, and individually definable business engineering building blocks at different levels of granularity, supporting the effective generation of (generic) enterprise models [13]. They in turn could be useful not only for enterprise engineers (for the sake of better understanding the operation of an enterprise, (re-)engineering an enterprise, and so on) but also for software engineers (for the sake of methodologically generating software specifications). Such building blocks may be instrumental when it is needed to:

- capture generic functionality pieces and use them in multiple cases, parameterizing them accordingly;

- compose complex solutions – this would be more effective and easier when bringing together numerous “pre-fabricated” building blocks, rather than starting from the scratch;
- create designs where traceability and replaceability are possible.

Those strengths have inspired us to consider the BUILDING BLOCK concept also with regard to composing solutions for fallback behaviors in context-aware systems.

4.2 The Context of Context Awareness

As mentioned already: in the current paper, we only focus on situations that have been foreseen at design time, even though there are no design-time preparations for them. Still, with regard to “foreseen at design time”, we assume that at design time, a corresponding ACTION PROCESS has been “planted” in the context-aware system. At the same time, the system does not have “own resources” to fully realize the action process (because there are no design-time preparations) and would possibly need to count on “global” service support in order to deliver an adequate fallback behavior at real time. Hence, we introduce the labels “local” and “global” in this regard:

- LOCAL concerns information that is specific to the system and/or the system user(s), for example: the abovementioned action process, location/timing data concerning the user, and so on.
- GLOBAL concerns information that has a broader scope, for example: highway-traffic-related data, legal data, and so on.

Hence, superimposing the context-aware-system perspective and the building-block concept (see the previous Sub-section) inspires the need of considering LOCAL BUILSING BLOCKS and GLOBAL BUILDING BLOCKS.

At the same time, GRANULARITY is to be considered as well, with regard to those building blocks and we opt for addressing exactly two granularity levels, considering two corresponding labels, namely “b” and “B”:

- b (or low-grained building blocks) are encapsulating something “atomic” (that cannot be de-composed), for example: user location data;
- B (or composite building blocks) are encapsulated something “composite” (that can be de-composed), for example: user situation data (this could be de-composed to data concerning the location of the user, data concerning the “current” activity of the user, and so on).

4.3 Proposed Architecture

Inspired by Dietz, according to whom an architecture is about <u>deliberately restricting the design freedom</u> [14], we present our suggested solution directions (in the form of a proposed architecture), by firstly by imposing restrictions/assumptions as follows: <u>A</u>. We abstract from those situations for which there are design-time preparations and also from those situations that were not even foreseen at design time. <u>B</u>. For each covered situation type (foreseen at design time) there is an ACTION PROTOCOL, “planted” in the system design. <u>C</u>. DATA concerning the system and the user, that is relevant to any *action protocol* is locally stored and kept available. D. As it concerns the real time realizations of *action protocols*, each instance is stored for ANALYTICAL purposed that are two-fold: D1. The instances are clustered, applying non-supervised Machine Learning [7]; D2. The needs during execution are considered as training data, for the sake of PREDICTING a need within a "new" instance [12]. This all, provided as FEEDBACK to designers, can help tuning and improving the *action protocols* as part of the system maintenance. E. Anything, concerning an *action protocol*, that the system cannot realize, is a matter of EXTERNAL SERVICES, utilized via Internet.

We do not claim exhaustiveness with regard to the above list of restrictions/assumptions, and we plan to continue exploring this in future research. Further, we reflect them in a proposed multi-layer ARCHITECTURE, as illustrated in Fig. 1, where we use labels elaborated as follows: L1 (standing for "Layer 1") – APPLICATION LOGIC; L2 (standing for "Layer 2") – INTEGRATION LAYER; L3 (standing for "Layer 3") – INTERFACE LAYER; L4 (standing for "Layer 4") – LOCAL BUILDING BLOCKS; L5 (standing for "Layer 5") – SYNCHRONIZATION LAYER; L6 (standing for "Layer 6") – GLOBAL BUILDING BLOCKS. In the remainder of the current Sub-Section, we will elaborate each of those layers accordingly.

4.3.1 Application Logic

What is important about this layer is that it "holds" all ACTION PROTOCOLS as well as relevant triggering/sensing information.

Let us consider the situation S3 (see the example provided in Sect. 3): An EMERGENCY PROTOCOL may look like this: 1. Identify an emergency label ("fire" or "car crash" or "health problem", and so on); 2. Collect LOCALLY relevant data, such as location, timing, degree of severity, and so on; 3. Identify what is MISSING to execute the protocol; 4. Reflect this in corresponding GLOBAL service composition; 5. Archive data for analytical purposes; … and so on. Further, possible TRIGGERS may be specified, such as coming from system sensors or coming form users, and so on.

4.3.2 Integration Layer

Staying "on top" of the Application Logic Layer, the Integration Layer is about establishing CONSISTENCY with regard to all diverse actions, some of which are local (realized within the system) and others - global (coming from outside), such that the action protocol is a coherent whole.

4.3.3 Interface Layer

In order to adequately facilitate integration (see above), it is necessary to properly establish the INTERFACES through which the different action "providers" would "speak" to each other.

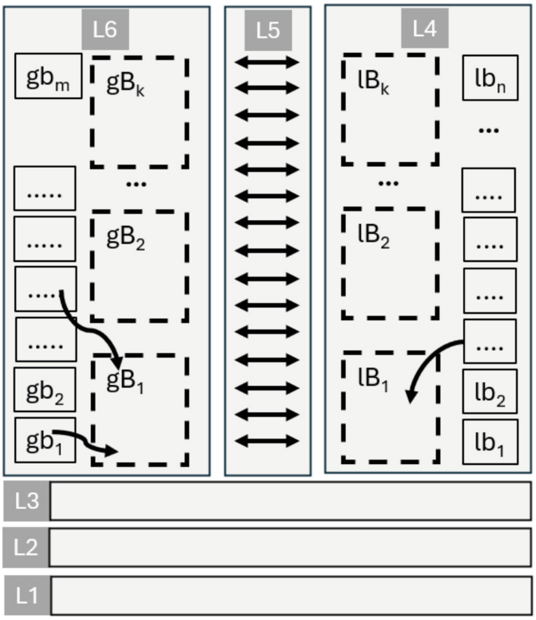

Fig. 1. Proposed Multi-Layer Architecture

4.3.4 Building Blocks (Layer 4 and Layer 6)

Aiming at architectural conciseness, we are considering exactly two levels of GRANULARITY with regard to *building blocks*: Level One (labelled "b" on the figure) that is "atomic" in the sense that such a building block cannot be de-composed further, for example: LOCATION MANAGER, TIME REGISTRATION MODULE, and so on; Level Two (labelled "B" on the figure) that concerns such *building blocks* that reflect an action from a corresponding *action protocol* but can be de-composed in terms of finer grained *building blocks*, for example: RELEVANT DATA COLLECTOR.

Let us now consider the LOCAL BUILDING BLOCKS layer (L4): lb_1 (local Level One building block 1), lb_2…, and lb_n are all local "atomic" *building blocks* – one is responsible for registering the time, another is responsible for registering the coach location (see the example), and so on; lB_1 (local Level Two building block 1), lB_2…, and lB_k are all local "composite" *building blocks*, receiving inputs accordingly from corresponding "atomic" *building blocks*. For example, the RELEVANT DATA COLLECTOR needs input from the building blocks registering time and location. A possible relation of this kind is illustrated by the arrow pointing to lB_1 on the figure. Hence, all those *building blocks* are about things that are LOCAL in the sense that are internal with regard to the context-aware system under consideration. The "composite" *building blocks* are a CONCEPTUALIZATION reflecting corresponding ACTIONS from the *action protocol*. Such a *building block* conceptualization is expected to be providing the right design restrictions for developing corresponding underlying SOFTWARE COMPONENT that would be actually running the *action protocol*. Further, it is important for the conceptualization to explicitly cover also the relations to corresponding "atomic" *building blocks* that are providing input accordingly. Finally, the potentials for feedback-driven refinements of *action protocols* (see above) is also important because this would contribute to maximizing the user-perceived effectiveness over time.

Let us now consider the GLOBAL BUILDING BLOCKS layer (L6): As it concerns granularity considerations and the conceptualization itself, things look similar to what was presented above, concerning L4. Nevertheless, they key differences are as follows: Firstly, the “composite” *building blocks* are not about restricting the design of underlying software components but they are about restricting DYNAMIC SERVICE COMPOSITIONS, in a service-oriented perspective; Secondly, the “atomic” building blocks concern SERVICE inputs from “outside”, again in a service-oriented perspective [15].

4.3.5 Synchronization Layer

On one hand, the global *building blocks* are about COMPLEMENTING corresponding local *building blocks* (in what they cannot deliver locally), and on the other hand, they concern “deliveries” that are of different origin (the local *building blocks* are about what the context-aware system itself is delivering while the global *building blocks* reflect service deliveries from “outside”). Hence, SYNCHRONIZATION with regard to both is essential, that in turn should go in combination with concerns that have already been discussed, namely integration and interfacing.

IN SUMMARY: The essence of the proposed architecture concerns the goal of adequately responding to a PRE-DEFINED *action protocol*, by MOBILIZING, SYNCHRONIZING, and INTEGRATING not only LOCAL but also GLOBAL “resources”.

5 Conclusion

Considering FALLBACK behaviors with regard to context-aware systems is claimed to be not enough explored and we have proposed relevant solution directions, namely a multi-layer architecture that COMBINES local (system-internal) and global resourcs, for the sake of fulfilling pre-defined action protocols that concern such behaviors. We expect that such innovative ideas would be usefully complementing the current context-awareness-related approaches that mostly count on rigorous design time preparations. From our research-in-progress perspective in this regard, we plan future research that would be focusing not only on further architectural elaborations but also on corresponding validations.

We are interested in considering MULTI-MODAL TRAFFIC as an application domain of high societal relevance (since more and more people and/or goods need to be transported in more and more ways), and in particular: DRONE TECHNOLOGY [16–18] because it is fast advancing as it concerns “autonomic behavior”.

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A Declarative Semantics for an Expressive Class of Well-Formed Activity Diagrams

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Abstract. *Context*: Activity Diagrams visualize sequences of instructions, including control flow. They are important and popular for modelling the dynamics of a (workflow) system. We address the problem of their unclear specifications.

Problem: The semantics of Activity Diagrams is usually only given informally, e.g., in natural language, by means of concrete examples, via ontologies, or via some kind of *operational* semantics, usually limited to the flow of control only. For informal sketches in a discussion, this is okay. But as a vehicle for precise system specifications this is not sufficient. There exists no suitable mathematical, declarative semantics for Activity Diagrams in terms of state changes achieved.

Research goal: To specify an unambiguous and mathematically sound declarative semantics for Activity Diagrams.

Solution: Starting from the expressive class of well-formed Activity Diagrams defined earlier, we develop a declarative semantics for those Activity Diagrams in a syntax-driven way.

Additional contribution: This novel idea and principles are generally applicable for other kinds of diagrams too, e.g., for Business Process Modeling diagrams.

Keywords: Activity Diagram · Well-Formed · Action · Instruction · Grammar · Production Rule · State Change · Meaning · Declarative Semantics

1 Introduction

Activity Diagrams visualize sequences of actions to be performed [1]. They are important for modelling the dynamic aspects of a system [2]. A standard for Activity Diagrams is provided by UML. The objective of UML is "*to provide system architects, software engineers, and software developers with tools for analysis, design, and implementation of software-based systems as well as for modelling business and similar processes*" ([2], p.1). Besides backward references, [2] also has many *forward* references. This (and other issues) makes the UML-specification hard to follow. The relevant problem with Activity Diagrams to be tackled in this paper is the following:

Lack of a Clear Meaning. The semantics of Activity Diagrams is usually only given informally, in natural language or by means of concrete examples (e.g., [1, 3]),

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via ontologies (e.g., [4–7]), or via some kind of operational semantics. Their meaning is not always clear. For instance, what does Fig. 1 mean (in terms of the meanings of A, B, C, D, and the condition)? The lack of a clear meaning leads to various implementations, that behave differently [8]. In those cases, the implementation determines the meaning.

The comprehensive definition of UML in [2] states under Scope (page 1): "*The semantics define, in a technology-independent manner, how the UML concepts are to be realized by computers*". This is not a mathematical, declarative semantics but at best an operational semantics. As [1] and [9] already noted, the syntax and semantics of Activity Diagrams are not even fully defined in UML (e.g., with 'semantic variation points'). In [2], there are many sections called 'Semantics' but there is no clear formal semantics in terms of state changes achieved. Although 'The effect of one ActivityNode on another is specified by the *flow of tokens* over the ActivityEdges between the ActivityNodes' (Sect. 15.2.3.1 in [2]), this specifies only the flow of control (using Petri-nets), but does not specify the corresponding state change. Moreover, Petri-nets are imperative [10].

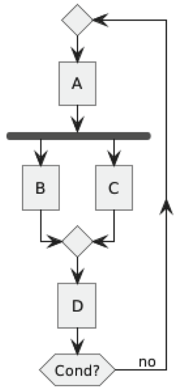

Fig. 1. What does this mean?

We will not need Petri-nets. Our central question is:

What does an Activity Diagram exactly mean? And what *doesn't* the Activity Diagram say (but maybe only suggest)?

Our Approach: A Declarative Semantics for Activity Diagrams. A declarative semantics for process diagrams is very unusual, to say the least. In the current paper, we define a mathematical, declarative semantics for the class of well-formed Activity Diagrams that is defined in [11]. This leads to a clear and relatively simple semantics, compared to the ones in [10], for instance. The chosen subclass includes the most important and most frequently used constructs [10, 12].

By exploiting the similarities between UML Activity diagrams and BPMN (Business Process Model and Notation), we currently work out something similar for BPMN, which is an alternative way of representing workflows graphically.

The rest of the paper is organized as follows. Background-Sect. 2 (plus Appendix 1) recall the class of *well-formed* Activity Diagrams introduced in [11], which makes the current paper more self-contained. In order to understand the paper better, the underlying novel ideas and principles of a *declarative semantics* for actions and instructions are informally explained in Sect. 3. Section 4 contains the auxiliary mathematical definitions which are necessary for Sect. 5. In Sect. 5 we define the (subtle) formal declarative semantics of well-formed Activity Diagrams, the core scientific contribution. Section 6 mentions our conclusions and contributions. Appendix 1 contains the production rules that define our class of well-formed Activity Diagrams. Finally, Appendix 2 contains an illustrative example, in which almost all constructs appear.

2 Background: An Expressive Class of Well-Formed Activity Diagrams

In [11], we defined a class of *well-formed* Activity Diagrams, by means of production rules for diagrams (a ‘grammar’). Appendix 1 recalls those production rules, while Appendix 2 contains an illustrative example. The production rules presuppose *Basic Instructions* and *Basic Conditions* concerning the application at hand.

The grammar starts with 4 elementary constructs, known as *Sequential composition*, *Alternative*, *Conditional*, and *Option* (1st table in Appendix 1). The *XOR-split and -join* (choice) and the *AND-split and -join* (arbitrary order) are two other important constructs (2nd table in Appendix 1). For the well-formedness of the Activity Diagrams, it is important that the split and corresponding join appear together, in pairs! This condition is also important to give them a clear semantics.

There are two *loop-constructs*, representing a **while**-loop (0 or more times) and a **repeat**-loop (1 or more times): See F7 and F8 in the 3rd table in Appendix 1. Theoretically, only one of these two loop-constructs would be enough because the loop-constructs can be converted into each other.

There are also the powerful constructs of *declarations* and *calls* (a.k.a. ‘Includes’) of sub-processes (F9 and F10 in the 3rd table in Appendix 1).

Finally, an Activity Diagram preceded by an explicit start symbol and followed by an explicit stop symbol is called a *Finished Diagram* (Fig. 5 in Appendix 1).

As explained in [11], many other constructs can be caught with these basic constructs too. For instance, the so-called *OR-split and -join* can be considered as an *AND-split and -join* with conditionals as ingredients. Exception possibilities and all ‘binary’ examples can also be treated with those constructs. Altogether, this class of well-formed Activity Diagrams forms an expressive, powerful class [12]. The constructs are inspired by the constructs in programming languages and validated in various applications [11].

Flow of Control. As recalled in Appendix 1, the flow of control (i.e., the order in which individual instructions are executed or evaluated) is always simple within well-formed Activity Diagrams: In each diagram, the flow of control will ‘run’ from the top towards the bottom. Alternatively said, the flow of control follows the arrows [11].

3 Declarative Semantics of Actions and Instructions Explained Informally

We distinguish between an **instruction** (often a part of a *standard operating procedure*) and an **action**, i.e., a particular execution of the instruction. Typically, an action has a start time, while an instruction hasn’t. A *standard operating procedure* is described as a set of step-by-step instructions compiled by an organization to help workers carry out (routine) operations.

Before we formally define the *declarative semantics* for actions and instructions in Sect. 5, we informally explain the general idea and principles of such a declarative semantics in this section.

Loosely speaking, we consider the declarative semantics of an *individual action* to be the state transition it achieved, i.e., from the 'old' state to the 'new' state. Therefore, we will model the *declarative semantics* of an *individual* action as a *state transition*, i.e., a pair of states (s; s'), where s is called the 'old' state and s' the 'new' state of the state transition. We call (s;s) a 'no-step-transition', i.e., if the new state is the same as the old state. To make our approach generally applicable, the notion of 'state' is taken as primitive in the general theory. In concrete applications, states must be made concrete; see for instance the example in Appendix 2.

Initially, we might be inclined to model the declarative semantics of an *instruction* as a function, a function that assigns to any ('old') state a ('new') state. However, an instruction can be <u>non-deterministic</u> (e.g., 'Either do A or do B'). So, we model the *declarative semantics* of an *instruction* as a <u>relation</u> (i.e., a set of ordered pairs), namely *the set of possible transitions* that that instruction can achieve. We call that relation the **transition relation** of that instruction. We note that 'executing a non-deterministic instruction' corresponds to choosing one of the possible 'new' states as the next state.

To link *Activity Diagrams* to declarative semantics, an 'interpretation function' m is introduced: For an Activity Diagram D, m(D) can be read as the <u>meaning</u> of D, where m(D) is the transition relation representing the set of all of possible transitions that Activity Diagram D represents.

To link a *condition* in a diagram to declarative semantics, we can use the classical 'interpretation function' from logic, i.e., a function assigning a 1 or a 0 to a state, indicating whether that condition is true or false in that state. During the execution of an instruction, the conditions are evaluated ('true' or 'false'), i.e., typically valuated by a human actor or computed by a machine as actor.

For each *basic* instruction in an application, its *transition relation* (the set of possible transitions that that instruction can achieve) must be determined for that application. Typically, the organisation for which the application is meant, must indicate that (to a requirements engineer, for instance). Our paper does not (and of course cannot) provide a semantics for basic instructions and basic conditions which are application-specific.

For a deterministic instruction, it suffices to express for each state the 'new' state only. E.g. for the instruction *Register Student with name n, address a, and birth date d*, the 'new' state might be the 'old' state with one extra student, having *name n, address a,* and *birth date d*, or the state will stay the same (if constraints would be violated).

4 Auxiliary Definitions

Before we can give the formal declarative semantics, we need a few general auxiliary definitions and terminology. We use the symbol '$\stackrel{\text{def}}{=}$' to mean 'is defined as'.

- If U is a set then: <u>id(U)</u> $\stackrel{\text{def}}{=}$ { (s;s) | s ∈ U }, called the **identity function** on set U
- If R is a relation (i.e., a set of ordered pairs), then:
  <u>dom(R)</u> $\stackrel{\text{def}}{=}$ { x | (x;y) ∈ R }, called the **domain** of R. /* so, all its 1st coordinates
  <u>rng(R)</u> $\stackrel{\text{def}}{=}$ { y | (x;y) ∈ R }, called the **range** of R. /* so, all its 2nd coordinates
- If R1 and R2 are relations then <u>R1 □ R2</u>, the **composition** of R1 with R2, consists of all the 'combinations' of transitions in R1 'interlinked with' transitions in R2:
  <u>R1 □ R2</u> $\stackrel{\text{def}}{=}$ {(x;z) | ∃y∈dom(R2): (x;y) ∈ R1 and (y;z) ∈ R2}.
  We note that composition is *associative*, i.e., R1 □ (R2 □ R3) = (R1 □ R2) □ R3; so brackets are not really needed
- If R is a relation then:
  $R^0 \stackrel{\text{def}}{=} \mathrm{id}(\mathrm{dom}(R))$ /* the set of all '0-step' transitions in R
  $R^{n+1} \stackrel{\text{def}}{=} R^n \,\square\, R$ /* set of all transitions possible in R in n+1 steps ($n \geq 0$)
  $R^* \stackrel{\text{def}}{=} \bigcup\{ R^n \mid n \in \mathbb{N} \}$ /* set of all transitions possible in R in 0 or more steps (a.k.a. the **transitive closure** of R)
- If U is a set, $R \subseteq U \times U$ (i.e., R is a relation on U) and $f : U \rightarrow \{0,1\}$ (i.e., f is a function from U to {0,1}), then:
  <u>$R \restriction^{+} f$</u> $\stackrel{\text{def}}{=}$ { (x;y) ∈ R | f(x) = 1 }, called the **positive limitation** of R by f
  <u>$R \restriction^{-} f$</u> $\stackrel{\text{def}}{=}$ { (x;y) ∈ R | f(x) = 0 }, called the **negative limitation** of R by f

Here, R typically represents the meaning m(D) of an Activity Diagram D, while f typically represents the interpretation function of a condition C, i.e., the function assigning 1 or 0 to a state x, indicating whether condition C is true or false in state x.

5 Formal Declarative Semantics for Well-Formed Activity Diagrams

We define a function m that assigns a declarative semantics to all well-formed Activity Diagrams. The relation m(D) will be the set of all of possible transitions that Activity Diagram D represents. We do this by following the construction rules given by the figures in Appendix 1. We recursively define the meaning of a composite diagram in terms of the meaning of its direct constituents. Below, v(C) is a function assigning a 1 or a 0 to a state s, indicating for state s whether condition C is true or false in state s.

If the resulting Activity Diagram of a construction rule is denoted by D then:

In F1: $m(D) \stackrel{\text{def}}{=} m(D1) \square m(D2)$
In F2: $m(D) \stackrel{\text{def}}{=} (m(D1) \upharpoonright^{+} v(C)) \cup (m(D2) \upharpoonright^{-} v(C))$
In F3: $m(D) \stackrel{\text{def}}{=} (m(D1) \upharpoonright^{+} v(C)) \cup (id(U) \upharpoonright^{-} v(C))$
In F4: $m(D) \stackrel{\text{def}}{=} m(D1) \cup id(U)$
In F5: $m(D) \stackrel{\text{def}}{=} m(D1) \cup m(D2) \ldots \cup m(Dn)$
In F6: $m(D) \stackrel{\text{def}}{=} \bigcup\{ m(p) \mid p \text{ is a permutation of } D1; D2; \ldots; Dn \}$
In F7: $m(D) \stackrel{\text{def}}{=} (m(D1) \upharpoonright^{+} v(C))^{*} \square \{ (s;s) \mid s \in U \text{ and } v(C)(s) = 0 \}$
In F9: $m(D) \stackrel{\text{def}}{=} m(P)$

To support validation, we give some explanation per construction rule:

Ad F1: According to the definition and explanation of '$\square$' in Section 4, $m(D1) \square m(D2)$ consists of the compositions of all transitions achievable by D1 'interlinked with' all transitions achievable by D2:

$$m(D1) \square m(D2) \stackrel{\text{def}}{=} \{(x;z) \mid \exists y \in dom(\, m(D1)\,): (x;y) \in m(D1) \text{ and } (y;z) \in m(D2)\}$$

Ad F2: According to the definitions of '$\upharpoonright^{+}$' and '$\upharpoonright^{-}$' in Section 4, $(m(D1) \upharpoonright^{+} v(C)) \cup (m(D2) \upharpoonright^{-} v(C))$ consists of all transitions achievable by D1 when condition C is true, and all transitions achievable by D2 when condition C is false

Ad F3: According to the definitions of '$\upharpoonright^{+}$' and '$\upharpoonright^{-}$' in Section 4, $(m(D1) \upharpoonright^{+} v(C)) \cup (id(U) \upharpoonright^{-} v(C))$ consists of all transitions achievable by D1 if condition C is true, and the 'no-step-transitions' in all cases where condition C is false

Ad F4: The union $m(D1) \cup id(U)$ consists of all transitions achievable by D1 and all 'no-step-transitions'

Ad F5: The union $m(D1) \cup m(D2) \ldots \cup m(Dn)$ consists of all transitions achievable by D1, by D2, …, or by Dn

Ad F6: For n different components, there are n! permutations. For instance, for n = 2:

$$m(D) \stackrel{\text{def}}{=} (m(D1; D2)) \cup (m(D2; D1)) = (m(D1) \square m(D2)) \cup (m(D2) \square m(D1)).$$

In general, $\bigcup\{ m(p) \mid p \text{ is a permutation of } D1; D2; \ldots; Dn \}$ consists of all transitions achievable by any permutation of D1; D2; …; Dn

<u>Ad F7</u>: Let R1 be the first part of the definition, i.e., $R1 = (m(D1) \upharpoonright^{+} v(C))^{*}$.
Applying the definition of '$\upharpoonright^{+}$', we get: $R1 = (\{ (x;y) \in m(D1) \mid v(C)(x) = 1 \})^{*}$.
In words: R1 consists of the results of all sequential compositions of all D1-pairs for which C is true in the 1st coordinate.

So, $m(D) = R1 \square \{ (s;s) \mid s \in U \text{ and } v(C)(s) = 0 \} = \{ (x;y) \in R1 \mid v(C)(y) = 0 \}$.
In words: m(D) consists of the results of all sequential compositions of all D1-pairs for which C is true in the 1st coordinate, while C is false in the final state of the composition

<u>Ad F8</u> (**repeat**-loop): A **repeat** can be rewritten as a **while**:

repeat S **until** C $\equiv$ S**; while not** C **do** S **end**

In this way we can obtain the meaning for F8 (and 2 times eliminate the **not** in **not** C):

For F8: $m(D) \stackrel{\text{def}}{=} m(D1) \square (m(D1) \upharpoonright^{+} v(\textbf{not } C))^{*} \square \{ (s;s) \mid s \in U \text{ and } v(\textbf{not } C)(s) = 0 \}$
$= m(D1) \square (m(D1) \upharpoonright^{-} v(C))^{*} \square \{ (s;s) \mid s \in U \text{ and } v(C)(s) = 1 \}$

In words, similar to F7, m(D) consists of the results of the composition of all D1-pairs with all sequential compositions of all D1-pairs for which C is false in the 1st coordinate, while C is true in the final state of the composition

<u>Ad F9</u>: Applying the definitions under F9 and F10 in Appendix 1, we get:

$m(\text{P}) \stackrel{\text{def}}{=} m(P) \stackrel{\text{def}}{=} m(D1)$, where D1is the diagram the name P stands for

Hence, m(P) consists of all transitions achievable by D1

Note that the semantic definitions confirm that the order of the D1, D2, ..., Dn in the XOR-split and -join (F5) and AND-split and -join (F6) is irrelevant.

It directly follows from the semantic definitions that the only relevant property of an arrow is its direction (Does the arrow go from A to B or from B to A?); all other graphical properties such as its length, thickness, curvature, or colour are irrelevant.

6 Conclusions and Contributions

We addressed the problem of UML's unclear informal specifications. We answered our research question by specifying an unambiguous, mathematically sound, declarative semantics for an expressive, powerful, and frequently used class of Activity Diagram constructs. Such a declarative semantics for process diagrams is novel.

We made use of the novel idea, introduced in [11], to (recursively) specify a well-defined class of well-formed Activity Diagrams by means of a grammar, as a basis to assign an unambiguous, mathematical, declarative semantics to all of them. In this way, the diagram constructs have a clear declarative semantics in terms of state changes achievable. Although it is common to present business process theories by means of examples only, we developed a general theory, not just a 'theory-by-example'.

The paper provides a well-defined subset of meaningful Activity Diagrams within the unclear, hardly restrained class of 'all' Activity Diagrams (which include meaningless Activity Diagram constructs).

The treated issues (and our solution) are not UML-specific but are more broadly applicable. E.g., currently, we work out something similar for BPMN, an alternative way of representing workflows graphically.

We also want to extend our notion of well-formed Activity Diagrams and provide those extension(s) with an unambiguous mathematical, declarative semantics as well, e.g., with constructs regarding 'time' (such as timers and timer events).

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Appendix 1: Production Rules and Semantics for Well-Formed Activity Diagrams

The tables on the next page recall the production rules from [11] to construct composite Activity Diagrams from given Activity Diagrams, as well as their semantics. This appendix constitutes a kind of ‘quick reference guide’.

Each column in each table subsequently contains (1) the common name of the composition rule, (2) the composite Activity Diagram, (3) its meaning (informally expressed), and (4) its formal declarative semantics as defined in Sect. 5. All Activity Diagrams ‘run’ from top to bottom.

Legend. In an Activity Diagram, a basic instruction B is represented in a rectangle with rounded corners, as shown in Fig. 2, a condition C is represented in a hexagon and followed by a question mark, as shown in Fig. 3, and an arbitrary Activity Diagram D is represented in a rectangle, as shown in Fig. 4.

Fig. 2. Basic Diagram for B

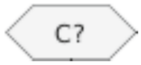


Fig. 3. Condition C

Fig. 4. Activity Diagram D

Finished Diagram. An Activity Diagram preceded by an explicit start symbol and followed by an explicit stop symbol is called a *Finished Diagram* (Fig. 5).

The semantics of a Finished Diagram is the same as the semantics of its Activity Diagram.

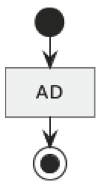
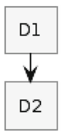
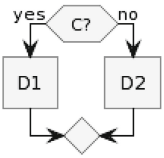
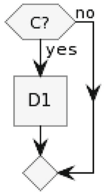
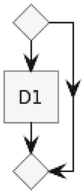


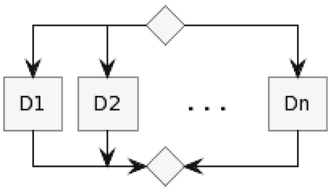
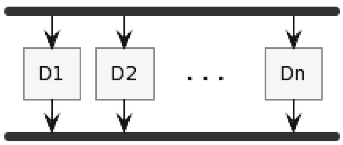
Fig. 5. Finished Diagram

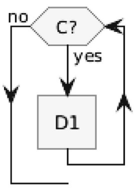
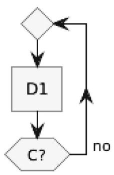
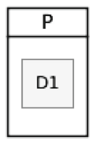
Flow of Control. In each well-formed Activity Diagram and each Finished Diagram, the flow of control is simple: In each diagram, the flow of control will ‘run’ from the top towards the bottom, i.e., the flow of control follows the arrows, as explained below.

In the diagrams in F7 and F8, the control flow starts at the top, goes 0 or more times through the loop, and ends at the bottom, *if it ends*: It might be that the loop never ends, namely if the condition stays true in F7 (**while**-loop) or stays false in F8 (**repeat**-loop).

The flow of control in each of the diagrams in F1 – F9 starts at the top and goes towards the bottom. In the diagram in F5, the control flow ‘goes through’ just one of the diagrams D1, …, Dn. In the diagram in F6, the control flow ‘goes through’ all the diagrams D1, …, Dn, after which there is one single flow of control left.

F1. Sequential composition	F2. Alternative	F3. Conditional	F4. Option
			
First do D1, then do D2	If condition C holds, then do D1 else do D2	If condition C holds, then do D1 else skip D1	Do D1 or skip D1
m(D1) □ m(D2)	(m(D1) $\upharpoonright^{+}$ v(C)) ∪ (m(D2) $\upharpoonright^{-}$ v(C))	(m(D1) $\upharpoonright^{+}$ v(C)) ∪ (id(U) $\upharpoonright^{-}$ v(C))	m(D1) ∪ id(U)

F5. Choice (XOR-split and -join)	F6. Arbitrary order (AND-split and -join)
	
Do exactly one of D1, D2, …, Dn	Do each one of D1, D2, …, and Dn, in arbitrary order
m(D1) ∪ m(D2) … ∪ m(Dn)	∪{ m(p) | p is a permutation of D1; D2; …; Dn }

F7. **while**-loop	F8. **repeat**-loop	F9. Call (‘Include’)	F10. Declaration
			
While condition C holds, do D1	Do D1 until condition C holds	Perform the action(s) P stands for	The (process) name P stands for D1
(m(D1) $\upharpoonright^{+}$ v(C))* □ {(s;s) | s ∈ U and v(C)(s) = 0}	m(D1) □ (m(D1) $\upharpoonright^{-}$ v(C))* □ {(s;s) | s ∈ U and v(C)(s) = 1}	m(P)	m(P) $\stackrel{def}{=}$ m(D1)

Appendix 2: An Illustrative Example

We use the realistic example from [11] in which almost all constructs appear.

The main process starts with *Receive Order* and ends with *Close Order* (Fig. 6a): After receiving an order, the customer might be called for clarification (but not necessarily). Then two processes take place ‘in parallel’: (a) Preparing and delivering the order and (b) Handling the payment. When all that is finished, the Finance department is informed if (and only if) the amount was more than €5,000. Then the order is closed.

The sub-processes *Pick Order* and *Deliver Order* are worked out in further detail in Figs. 6b and 6c, respectively: *Pick Order* expresses to add products as long as the order is incomplete. *Deliver Order* contains an explicit decision between regular and rush-deliveries. A rush-delivery will be either by electric car or by motorcycle.

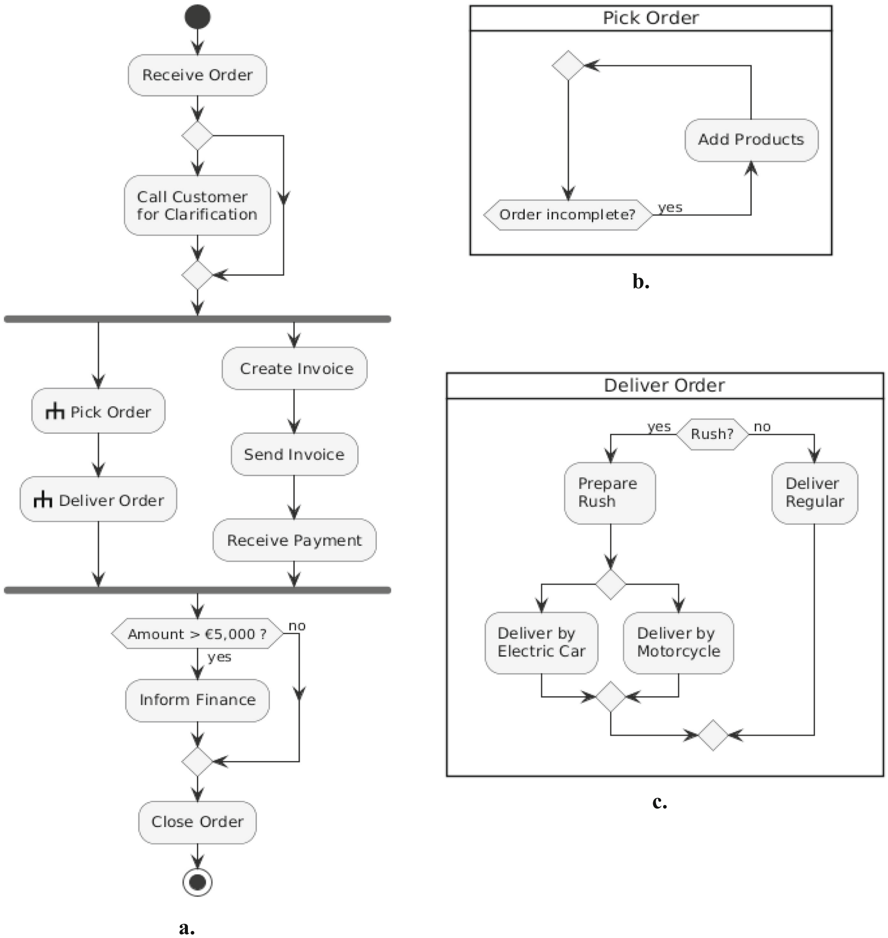


Fig. 6. (**a**) Main process. (**b**) Sub-process *Pick Order*. (**c**) Sub-process *Deliver Order*

State Changes by Basic Steps. According to the organisation at hand, the new state of each *basic* step in the main process (Fig. 6a) should be as described below, though only for the *Main Success Scenario* (a.k.a. the 'happy scenario'). That is, if everything runs 'normal', e.g., all ordered products were in stock, the products could all be delivered, the received payment indeed equals the amount of the corresponding invoice, etc.

Basic step	**New state (post-condition)**
Receive Order	Order list now contains that new order, with status 'Open'
Call Customer for Clarification	*Remarks*-field of that order might now be adapted
Pick Order	The ordered products (copies) are now at Logistics and not in stock anymore
Deliver Order	The ordered products are with the customer now
Create Invoice	The invoice list now contains that new invoice and that invoice has status 'Open'
Send Invoice	That invoice is sent to the customer and got status 'Sent'
Receive Payment	The company account is increased by the amount for that invoice, and the invoice now has status 'Paid'
Inform Finance	The Finance-department now has a message about that invoice and its amount (being > €5,000)
Close Order	*Status*-field of that order now has value 'Closed'

This already sheds some light on the relevant state structure and relevant state changes for the application. From the description, we can already deduce some of the relevant ingredients of (and requirements for) what constitutes a state in our running example:

- States must contain an order list, an invoice list, company account, location info about (ordered) products (e.g., 'in stock', 'at Logistics', 'at customer'), and messages at the Finance-department
- Orders must contain a *Remarks*-field and a *Status*-field (with values such as 'Open' and 'Closed')
- Invoices must contain a *Status*-field (with values such as 'Open', 'Sent', and 'Paid')

Declarative Semantics of the Constructs

Using the rules from Sect. 5, the declarative semantics of the composite constructs can now be derived. We work it all out step-by-step. We start with the *Main process*:

1. Declarative Semantics of the *Main process* (Fig. 6a)
Let CC4C be the Call Customer *option* in Fig. 6a, Split be the *AND-split and -join* in Fig. 6a, Order be the left hand side of Split, Fin be the right hand side of Split, and Amnt be the *conditional* near the end of Fig. 6a. Then:

m(Main process) = m(Receive Order) □ m(CC4C) □ m(Split) □ m(Amnt) □ m(Close Order),
where m(CC4C) = m(Call Customer for Clarification) ∪ id(U),
m(Amnt) = (m(Inform Finance) $\upharpoonright^+$ v(Amount > €5,000)) ∪
(id(U) $\upharpoonright^-$ v(Amount > €5,000)), and
m(Split) = (m(Order) □ m(Fin)) ∪ (m(Fin) □ m(Order)),
where m(Order) = m(Pick Order) □ m(Deliver Order) and
m(Fin) = m(Create Invoice) □ m(Send Invoice) □ m(Receive Payment).

2. Declarative Semantics of *Pick Order* (Fig. 6b)
m(Pick Order) = (m(Add Products) $\upharpoonright^+$ v(Order incomplete))* □
{ (s;s) | s ∈ U and v(Order incomplete)(s) = 0 }

3. Declarative Semantics of *Deliver Order* (Fig. 6c)
Let DR1 be the left hand side of Fig. 6c and let DR2 be the choice within DR1. Then:
m(Deliver Order) = (m(DR1) $\upharpoonright^+$ v(Rush)) ∪ (m(Deliver Regular) $\upharpoonright^-$ v(Rush)),
where m(DR1) = m(Prepare Rush) □ m(DR2),
where m(DR2) = m(Deliver by Electric Car) ∪ m(Deliver by Motorcycle)

Let us consider m(Fin), for example, which is the set of all of transitions that can be achieved by the right hand side of the AND-split in Fig. 6a. That part is typically deterministic, so with each 'old' state one 'new' state is associated. Following the earlier description under *State Changes by Basic Steps*, that new state is the old state except that the invoice list now contains that new invoice ~~with status 'Open'~~, that invoice is sent to the customer ~~and got status 'Sent'~~, the company account increased by the amount for that invoice, and that invoice has status 'Paid'. (The intermediate states with status 'Open' and with status 'Sent' for that invoice have meanwhile been replaced.)

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Software Architecture for Automated 3D Image Measurements

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Abstract. This paper presents a software framework for estimating the real-world dimensions of objects captured in video frames using monocular camera input. The system integrates feature tracking, multi-view geometry, and triangulation techniques to reconstruct 3D information from 2D video sequences. By incorporating a reference object for scale calibration, the framework enables accurate object size estimation without the need for specialized hardware. This approach is particularly suited for drone-based surveillance and automated inspection tasks in resource-constrained environments. The proposed solution concerns potential software strengths (in particular: hardware-independent object size estimation) that are expected to inspire usability-driven business process reengineerings, giving way to a cost-effective and less hardware-dependent real-time analysis for the benefit of decision-making in different application domains.

Keywords: Software architecture · Less hardware-dependent solutions · Object size estimation · Computer vision

1 Introduction

Context-aware information systems assume capabilities of "sensing" environmental changes and updating accordingly the system behaviour, often enabled by sensor technology [16–18]; current computer-vision-related technologies are considered promising in this regard, especially as it concerns object size estimation [1]. Determining the real-world dimensions of captured objects concerns the challenge to understand how a three-dimensional scene is projected onto the two-dimensional sensor of a camera [2]. In reality, this process involves a complex set of perspectives and geometric transformations.

On the one hand, the intrinsic parameters of the camera – such as focal length, principal point, and potential lens distortions – determine how the real-world coordinates of an object are transformed into pixel coordinates. On the other hand, the extrinsic parameters – namely the camera's position and orientation in space – influence the angle from which the scene is captured. The presence or absence of sensors for direct distance

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measurement – such as LiDAR or Time-of-Flight (ToF) sensors – can further complicate or simplify the computation of depth [3–5].

In real-world scenarios – such as aerial vehicles patrolling unknown or rugged terrain, or industrial systems for automated product inspection – it is often necessary to rely solely on a standard camera and apply mathematical algorithms to extract depth information from a sequence of images. This approach has been developed over the years within the field of multi-view geometry and enables the reconstruction of the three-dimensional structure of a scene by tracking and triangulating keypoints. Thus, even without additional hardware, the system can estimate the actual size of an object, provided that at least one reference scale is known or that the conditions for reliable reconstruction are met [6–8].

The current paper builds upon results reported at the previous edition of the BMSD symposium when we presented an object detection architecture enabling the detection of images and video streams based on color features; effectiveness was demonstrated in real-time object identification considered useful with regard to urban areas and beyond. Hence, we use those results as a bootstrap, aiming at adding the capability of automatically extracting three-dimensional information for detected objects [9]. We propose achieving this by means of multi-view geometry methods (Structure from Motion), such that we determine the actual physical dimensions and depth of captured objects, for example, objects captured by an Unmanned Aerial Vehicle (UAV). Our proposal is expected to enable significant improvements in areas, such as civil security and area/infrastructure monitoring.

We have addressed a number of challenges: from considering the simplified perspective projection model and pinhole camera, through tackling the general projection matrix formalism, to reconstructing multi-view algorithms and considering their application that concerns the determination of the real-world dimensions of objects. Along those lines, the paper presents practical guidelines for developing efficient solutions where the reconstruction of the actual scene geometry is required, using only accessible and standard tools.

The remainder of this paper is organized as follows: In Sect. 2 we consider the camera matrix. In Sect. 3 we analyze the depth determination achieved via a multi-view method with fixed scale. The achieved results are discussed in Sect. 4. Finally, we conclude the paper in Sect. 5.

2 Camera Matrix

A camera is a device that transforms the three-dimensional (3D) world around us into a two-dimensional (2D) image. This process is based on perspective projection, which simulates the way light passes through the camera's optical system and is projected onto the image plane [10, 11]. The primary function of the camera is to map each point in the real world (X, Y, Z) to its corresponding point in the image (x, y), while preserving information about spatial relationships and proportions. In computer vision, one of the fundamental and frequently encountered tasks is determining the actual dimensions of objects based on their images. This process requires an understanding of how the camera transforms a three-dimensional scene into a two-dimensional plane-and vice versa. In doing so, we encounter two fundamental challenges:

– The camera not only performs the projection but also alters the coordinate system of the spatial points, depending on its position and orientation in space.
– The transformation from 3D to 2D requires information about both the intrinsic characteristics of the camera-such as focal length and principal point-and its spatial position and orientation.

To describe this process with mathematical precision, matrices are used to encapsulate all the necessary information about the camera's characteristics and its spatial position.

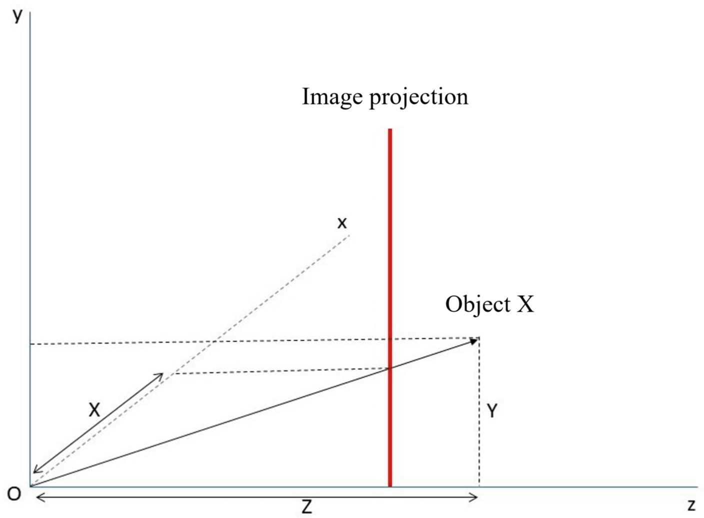

Fig. 1. Perspective projection in Pinhole camera model

Figure 1 illustrates the geometry of perspective projection, in which the camera projects the three-dimensional scene onto a two-dimensional image plane. The projection is described using the camera matrix, denoted as P as proposed in [2]. The sample object "Object X" has coordinates in 3D space given by $[X, Y, Z]$. This object is projected onto the image plane at the point (x, y). As shown in the figure, by applying the principles of similar triangles, we can derive the following equations for the coordinates of the 2D projection:

$$x = f\frac{X}{Z} \text{ and } y = f\frac{Y}{Z} \tag{1}$$

Alternatively, the expression in matrix form would appear as follows: $[X, Y, Z]^T \rightarrow [fX/ZfY/Z]^T$.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^T \rightarrow \begin{bmatrix} fX/Z \\ fY/Z \end{bmatrix}^T \tag{2}$$

These equations illustrate how the projection coordinates depend on the focal length (f) and depth perspective (Z). They form the basis of the simplified pinhole camera model, which shows how real-world coordinates (X, Y, Z) from the three-dimensional scene are transformed into two-dimensional coordinates. To fully describe the process of determining object dimensions in computer vision, it is necessary to use the so-called homogeneous or camera projection matrix P, , which provides the mathematical relationship between the intrinsic parameters of the camera, as described above, and the extrinsic (physical) parameters of the scene.

These extrinsic parameters are strictly determined by the physical position and orientation of the camera at the moment the scene is captured.

For a reliable representation of perspective projection, a point with coordinates X, Y, and Z is considered in three-dimensional space using homogeneous coordinates:

$$\widetilde{\chi} = [X, Y, Z, 1]^T \tag{3}$$

Similarly, any point in the image plane (x, y) can be represented using this formalism. From this, it logically follows that if the input coordinates are expressed in homogeneous form as a four-dimensional vector: $\widetilde{\chi} = \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \in \mathbb{R}\ 4$ and the output coordinates in the two-dimensional image plane are represented in homogeneous form as a three-dimensional vector: $\widetilde{\chi} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \in \mathbb{R}\ 3$. The perspective matrix P, which represents the linear normalization, should therefore be a matrix of size 3 by 4, so that $\tilde{x} = P\tilde{X}$, [2] where the final values of (x, y) are obtained by dividing by the third coordinate. Typically, the matrix P is considered as the product of two matrices [2]:

$$P = K[R|t] \tag{4}$$

where, K represents the intrinsic parameter matrix of size 3 by 3, which includes the focal lengths fx and fy, as well as the coordinates of the principal point (Cx, Cy). They define the position where the optical axis (an imaginary line passing through the center of the lens and perpendicular to the sensor) intersects the image plane. This is the central point around which the perspective projection unfolds. In an ideal model, it coincides with the geometric center of the sensor (i.e., the center of the image frame). Additionally, scale factors or distortion coefficients can also be considered here, especially when more complex camera models are used [1]. The matrix K has the following general form:

$$K = \begin{bmatrix} fx & 0 & Cx \\ 0 & fy & Cy \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

where $[R|t]$ are the extrinsic parameters, where R is a 3 by 3 rotation matrix that describes the orientation of the camera relative to the coordinate system, and t is a 3 by 1 translation vector that defines the position of the camera in space. In this case:

$$(Cx, Cy) = (0, 0) \text{ and } (fx, fy) = f \tag{6}$$

Since t is the zero vector and R is the identity matrix, we can conclude that the world coordinate system coincides with the camera coordinate system. The application of the projection matrix P makes it possible to trace the relationship between the physical dimensions of an object and its pixel dimensions in the image frame (x, y). To compute the actual dimensions of the object, it is essential to know the depth value Z or the scale factor under which the object is projected.

There are several possible approaches to determining the depth Z of a scene. The simpler method, which does not require complex computations or image calibration, involves the use of sensors that measure distance distributions per pixel or per point-such as Time-of-Flight (ToF) or LiDAR.

In the absence of such sensors or direct distance measurement techniques, there are mathematical methods and algorithms that can extract depth data using reference objects or known planar structures. Naturally, achieving measurement accuracy is considerably more difficult with these methods.

3 Depth Determination via a Multi-view Method with Fixed Scale

For the purposes of our application, we have employed a depth estimation algorithm based on capturing and tracking frames at the very beginning of the acquisition process. The core idea is that multiple frames captured from different positions and angles contain sufficient spatial information to recover the relative arrangement of points in three-dimensional space. If an object with known physical dimensions is captured during takeoff or at a selected moment, the resulting reconstruction can be scaled to real-world units to determine the absolute depth Z.

It is important to note that, due to the complexity of the computations and the resources required to perform them in real time, this method does not provide extremely high precision. However, it is sufficient for estimating the approximate dimensions of detected objects. In general, the algorithm we use consists of a set of methods aimed at reconstructing the three-dimensional structure of a scene and determining the motion parameters of the camera (its position and orientation), using multiple two-dimensional images captured by the same camera at different times or from different viewpoints.

Unlike stereo systems, where at least two cameras with a known baseline are used, in our case a single camera moves through space or observes the object from various angles, thereby accumulating enough parallax to allow for 3D reconstruction of the scene.

Figure 2 presents a flowchart of the algorithm we use for reconstructing three-dimensional structure and estimating real-world object dimensions from a monocular image sequence. Each step reflects the core processes – from the input video to the final size estimation. As shown, the reference object and the scaling factor are applied after the triangulation step to establish the absolute scale of the reconstruction.

Let us consider a sequence of n images, and denote the keypoints detected in k of them as $\{x_j^i\}$, where $i \in \{1, \dots \mathrm{N}\}$, where the index i denotes the individual keypoints in the scene, and j ∈ {1,…,k} – refers to the frames in which these points are tracked. Each

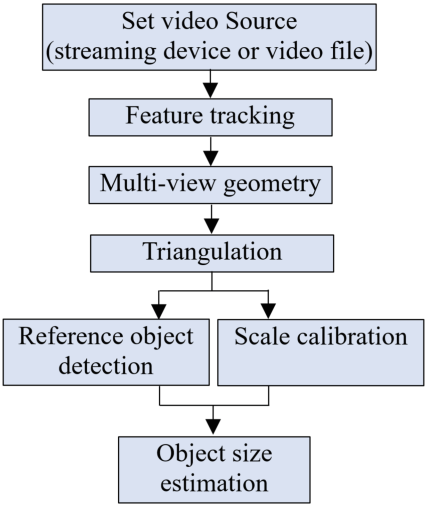

Fig. 2. Flowchart of the object size estimation process

point $\{x_j^i\} \in \mathbb{R}^3$. Each point is often represented in homogeneous form $\{\overset{\sim i}{\chi}_j\} \in \mathbb{R}^3$. A key component in depth reconstruction is the computation of the essential or fundamental matrix, which relates corresponding points between two images. When the camera is calibrated (i.e., the intrinsic parameters are known), the essential matrix E is used. In contrast, when the camera is uncalibrated, the fundamental matrix F is introduced. The fundamental matrix is associated with the epipolar constraint through the following equation [1, 2]:

$$\overset{\sim i+1T}{\chi_j} F \overset{\sim i}{\chi_j} = 0 \tag{7}$$

which shows that each pair of corresponding points lies on their respective epipolar lines in the two images [2]. When the intrinsic parameters are known, it is possible to work with the essential matrix $E = [t]_x R$, where R is the rotation matrix and t is the translation vector between the different camera positions. The operator $[t]_x$ represents the cross product with the vector t. Once the essential matrix E is computed, the rotation R and translation t can be recovered. After obtaining the rotation matrices R_j and translation vectors tj for each frame, the corresponding projection matrices $\{P_j\}$ are formed. Then, for each keypoint that is visible in at least two frames, triangulation is applied to determine its 3D position $X_i = (x_i, y_i, z_i)$. Linear triangulation formulates the system:

$$P_j \overset{\sim}{\chi}_i = \tilde{x}_j^i \tag{8}$$

where $\overset{\sim}{\chi}_i$ are the homogeneous coordinates of the three-dimensional point and $\tilde{x}_j^i$ represent the homogeneous coordinates of the corresponding two-dimensional projection. To improve accuracy, it is common to apply a nonlinear optimization step after the initial linear solution. This step is known as bundle adjustment, and it minimizes the total error between the observed two-dimensional projections and the reprojected ones, as proposed in [3].

As a result of this process, the 3D coordinates of the keypoints are reconstructed, and the extrinsic parameters (position and orientation) of the camera are determined for each frame within a common coordinate system. This makes it possible to extract the depth value Z for each triangulated point. If the scene contains sufficient visual features, a nearly dense reconstruction can be achieved using additional methods discussed in [1]. For areas with sparse correspondences or uncovered regions, interpolation is often applied.

One of the main challenges in the practical application of this method is the ambiguity of scale, as a monocular camera recovers structure only in relative units. When it is necessary to obtain real-world object dimensions, reference information-such as an object with known size or an external geodetic reference point-can be used to fix the absolute scale. This allows the system to determine whether an object is actually 5 m or 20 m wide, rather than simply four times wider than another object [1]. Such scaling proves particularly valuable in field conditions where stereo cameras, LiDAR, or other specialized depth sensors are not available. It is sufficient to capture an object of known dimensions at least once and to scale the entire reconstructed scene accordingly. In the model we propose, this is performed at the very start of the process. This approach, built on that principle, is especially suitable for drones operating in urban or uneven terrain, as it offers high flexibility and accuracy, provided that sufficient parallax and reliable keypoint correspondences are available [12–14]. Processing a sequence of frames from a moving camera enables continuous updates to the 3D information, and once the scale is fixed, it becomes possible to estimate the actual dimensions of objects that were not present in the initial calibration. Although the method requires considerable computational effort and robust point-tracking algorithms (such as SIFT or ORB), it delivers reliable accuracy and does not rely on pre-trained neural models for depth estimation [4, 15].

4 Results and Analysis

The implementation of the aforementioned methods in our system was carried out with the help of additional libraries, such as [5], which provide optimized algorithms to support triangulation calculations across multiple frames. Feature detectors and descriptors are used to identify and match unique and distinguishable objects across individual frames. This process involves two main stages: feature detection and feature matching.

Feature detection represents the initial step in image analysis, in which stable and locally distinctive regions of a frame are identified-regions that can be tracked or compared across different views of the same scene. These keypoints are typically found in areas with sharp intensity changes – such as corners, edges, textured surfaces, and zones with high contrast gradients. Such regions contain local characteristics that enable reliable matching between frames, even in the presence of small changes in scale, orientation, or lighting conditions.

After detecting keypoints, the next step is to match them across different images (feature matching), where for each point in one image, the best corresponding point in another is sought. This is done by comparing their descriptors – vector representations that describe the local structure around each point. Euclidean distance is most commonly used as a similarity measure between the vectors. To improve the reliability of the matches, the ratio test described in [9] is applied, requiring that the closest match be significantly closer than the second-best one. This helps eliminate ambiguous matches and ensures robustness against geometric and photometric transformations. This process is crucial for reliably establishing correspondences between images and underpins more advanced tasks such as scene reconstruction, localization, and motion tracking.

The integration of the current module for keypoint detection and matching into our previously developed object recognition software, described in [6, 7], has been achieved through the use of the Emgu CV library, which is already included in the application. This library provides access to the aforementioned algorithms and enables relatively accurate and efficient real-time processing of video frames. The results from processing a sequence of images are shown in Fig. 3.

Fig. 3. Results from Object Measurement Based on Triangulation (in cm)

At present, the measurements are performed manually, but integration of this functional module with the existing system for automatic object recognition based on their visual characteristics (shape and color) is forthcoming. The results shown are part of a composite scene built from two selected frames with different camera exposures. At the beginning of the process, the camera was calibrated using a reference object with known dimensions, which subsequently remained outside the field of view.

After the initial calibration is performed, the algorithm tracks geometric transformations between consecutive frames through triangulation and reconstructs the three-dimensional structure of the scene. This enables the calculation of the spatial dimensions of newly appearing objects. In the conducted real-world measurements, the deviation of the estimated values from the actual object sizes was within the range of 5–6%, which is considered fully acceptable given the intended application of the model.

The main goal of the system is to provide approximate information about the dimensions of objects in the scene – both to the human operator and to subsequent algorithms responsible for object classification and sorting. This is especially important when using a drone or other mobile device equipped with a camera, where the priority is not absolute metric precision, but timely and sufficiently reliable information for making decisions in a dynamic environment.

5 Conclusion and Future Work

Building upon previous work, we have proposed a vision-analysis-related innovation that is expected to inspire less-hardware-dependent software solutions enabling object size estimation, counting on a monocular video input. In achieving this, we have combined multi-view geometry, triangulation, and scale calibration, based on reference objects. The applicability of our proposed innovation concerns situations where specialized depth sensors are unavailable. Still, in a less-hardware-dependent way, practical and flexible solutions can be offered, for the benefit of UAV monitorings, autonomous inspection systems, and so on.

In future work we plan focusing on the goal of automating the scale calibration process through object recognition models, integrating semantic segmentation, for the sake of enhancing keypoint stability, incorporating decision-making components, and so on. We will also be aiming at optimizing the computational performance such that seamless operation is allowed on embedded systems. Finally, we would work for expanding the method's applicability to complex environments with partial occlusions and dynamic scenes.

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Ex-Ante Evaluation Approaches Within the Design Process of Information and Data Models

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Abstract. Ensuring semantic consistency and data integrity of information exchanges between these interconnected systems requires robust information and data models. As new models are emerging, it is essential to evaluate them during the design process. However, model developers often lack clear methods or guidelines for evaluating their new information and data models. We conduct a narrative literature review of academic publications to understand the current state. We generate a simple visual illustration mapping our focus in the context of information and data model evaluation with existing approaches to assist model developers in identifying suitable methods. Our findings highlight two main approaches for information models, while also identifying a gap in evaluation approaches for data models. Future work could focus on designing a combined approach for IMs & DMs to provide a structured guidance for model developers.

Keywords: evaluation · evaluation approaches · quality · quality characteristics · information model · data model

1 Introduction

The reliable exchange of information is fundamental to effective service interactions between information systems [1]. However, when the exchanged data is incorrect, incomplete, or inconsistent—whether due to flaws in the application logic or the underlying information and data model (IM & DM)—it compromises quality and disrupts intended outcomes.

As digitalisation progresses, the number and complexity of interconnected information systems increase, further intensifying this issue [2]. Especially as modern information systems increasingly rely on automated, machine-to-machine information exchange, which demands robust and standardised IMs & DMs to ensure semantic consistency and data integrity.

In response to these demands, domain-specific IMs & DMs are emerging to facilitate reliable data exchange playing a critical role in the digitalisation process. One example is the DM EEBus SPINE, used in smart homes and building

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automation in the energy sector. It defines structured messages and communication procedures for controlling and monitoring smart appliances [3], ensuring interoperability across diverse systems.

Given the critical role of IMs & DMs, it is essential to evaluate new IMs & DMs as they emerge during their design process [4]. This allows for an ex-ante evaluation, which helps capture design inconsistencies within models and services [5]. Ex-ante evaluation helps reduce potential costs associated with detection and correction [6], and positively impacts operational efficiency and service quality.

Despite the importance of evaluating new IMs & DMs during their design process, model developers often face the challenge that there is a lack of clear methods or guidelines for evaluating them [6]. For instance, considering the previous example of EEBus SPINE [3] and more generally, these do not report on their evaluation during their design phase limiting other developers to benefit from. In many occasions, model development, within specific sectors as the energy sector, might occur in silos with a focus on achieving robust designs only through fast implementations.

To contribute to a clearer, robust model design process and provide support for the evaluation of new IMs & DMs during their design process, we pose and address the following research question:

RQ: *What are the different existing approaches to evaluate newly designed IMs & DMs geared towards information exchanges between information systems?*

To answer this research question, we conduct a narrative literature review and identify, analyse and report on publications on the various evaluation approaches available to model developers. In addition, we generate a simple visual illustration mapping our focus in the context of IM & DM evaluation with existing approaches. Our findings highlight two main approaches for information models, while a gap in evaluation approaches for data models. Future work could focus on designing a combined approach for information and data models to provide a structured guidance for model developers.

We organise the remainder of the paper as follows. In Sect. 2, we introduce the definitions of the model types we consider in this paper. In Sect. 3, we describe our narrative literature review approach. In Sect. 4, we provide the result of our literature review. In Sect. 5, we discuss our findings and suggest potential future research directions. In Sect. 6, we conclude the paper.

2 Background: Definition of Model Types

Given the topic's complexity, we introduce the main definitions for our paper. We adopt the definitions by Pras and Schoenwaelder [7] as the basis because they clearly distinguish between IMs from DMs.

We understand IMs as models that define objects at a conceptual level, without including implementation- or protocol-specific elements [7]. They specify the semantics of data through a representation of concepts, relationships and rules for a specific domain [11]. Meanwhile, other definitions provide a wider and combined one. For instance, Olivé [8] describes conceptual models in information systems as *tools* for *"viewing domains in a particular way"*. Similarly, Krogstie [9] defines a conceptual model as *a domain model expressed* in a formal or semi-formal language.

In turn, we define DMs as models that operate at a lower level of abstraction and include implementation-specific details in line with [7]. These models specify the data symbols and data types to which information can be mapped [10]. DMs are commonly defined using schema languages such as Extensible Markup Language (XML) [10] or structured notations like JavaScript Object Notation (JSON). The result of mapping data to a specific DM is referred to as a DM instance. A single IM can be mapped to multiple DMs [11]. However, to ensure reliable information and data exchange, systems must agree on shared interpretation rules [12], which requires using the same DM.

3 Literature Review Approach

We conducted a narrative literature review from a software engineering perspective to provide an up-to-date overview of existing evaluation approaches related to IMs & DMs. We base our literature review approach on recommendations provided by Green, Johnson, and Adams [13], and the guidelines outlined in Paré et al. [14]. To enhance transparency and address common limitations associated with narrative reviews (i.e., where, what, and how searched), we further incorporated the recommendations of Snyder [15], developing a structured search and analysis protocol. While this protocol provides a clearly defined, step-by-step process, it is not intended to constitute a quantitative or systematic review reporting the number of papers in each step. The structured search and analysis protocol is as follows:

First, (1) we defined search terms and selected relevant databases. By combining the following search terms: *data model/information model* and *quality/evaluation/validation*, we aimed to capture a broad spectrum of evaluation approaches. To achieve this, we explored established databases, including IEEE, Scopus, and Google Scholar.

Second, (2) when searching for relevant literature, we focused on titles, abstracts, and keywords. We included peer-reviewed journal and conference publications written in English. In addition, we included only publications that focused primarily on model evaluation or model quality. We analysed the core components and the complete manuscript when deemed appropriate by the authors.

Third, (3) we enhanced our review using a "snowballing" approach as described by Callahan [16]. By tracking the references in previously found articles and examining the citations of these papers, we aimed to increase the effectiveness of our search and discover more relevant literature related to our topic. In total, we reviewed approximately 80 papers, but we only include those we deem fit. We provide the results in the following section.

4 Evaluation Approaches for Information and Data Models

Following our goal of finding the different existing approaches to evaluate new designed IMs & DMs geared towards automated information exchanges, we split our focus on the one hand into IM approaches and on the other hand on DM approaches. As a support, we provide a simple visualisation in Fig. 1. Our analysis revealed that existing evaluation approaches focus primarily on the evaluation of IMs according to our definitions in Sect. 2. For example, when we examined our considered literature, we observed the use of the DM term in such a way that aligns with our definition of IMs, as seen in Moody and Shanks [17]. In such a case, we map the literature to the IM type in our visual illustration. Consequently, we provide in Sects. 4.1 and 4.2, a deeper overview of the existing approaches.

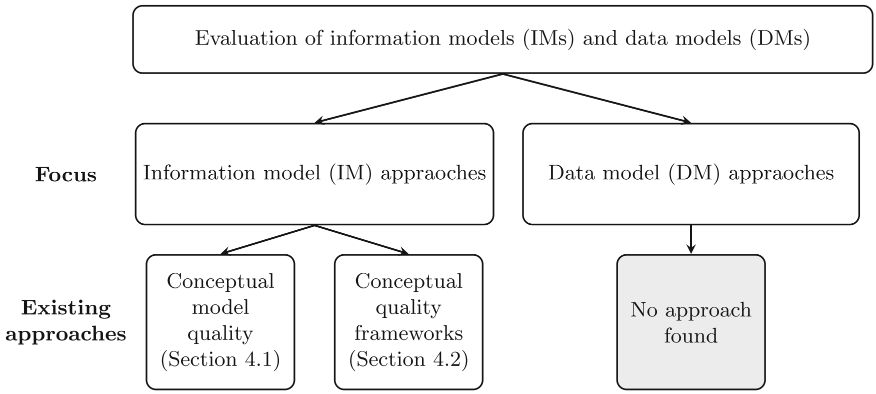

Fig. 1. Overview of approaches for evaluating IMs & DMs.

4.1 Conceptual Model Quality

Moody [6] defines conceptual model quality as the *"totality of features and characteristics of a conceptual model that bear on its ability to satisfy stated or implied needs"*. In our paper, we refer to these characteristics as quality characteristics (QCs) [18]. The literature also refers to the terms: quality factors [17], quality goals [19], quality types [20] or quality levels [21].

We provide in Table 1 an overview of the analysed literature and map each work to its type of QC representation. We distinguish between representations structured as theoretical frameworks and those presented as lists. Theoretical frameworks relate multiple QCs to each other, while lists do not do it. For example, Lindland, Sindre, and Solvberg [19] define and link model quality using four QCs (termed quality goals) grounded in linguistic theory. They also introduce the concept of feasibility, noting that modelling does not end with the achievement of ideal quality. Instead, feasible quality requires balancing benefits and drawbacks. This framework builds the basis for further extensions and refinements.

The SEQUAL framework expands the number of quality goals—referred to as quality levels [21]. These levels integrate various perspectives on model quality and are grounded in semiotic theory, the study of signs and their meanings.

Similarly, the CMQF framework builds upon the work of Lindland, Sindre, and Solvberg [19] and further extensions and combined it with an ontological model by Wand and Weber [22]. The CMQF framework defines twenty-four QCs and maps them to four layers representing the basic modelling process and the object of interest. Since we address the evaluation of IMs & DMs as the result of the modelling process, we only focus on the QCs mapped to the "physical representation".

All three theoretical frameworks [19–21] mention syntactic correctness or syntactic quality as one QC making it as one of the most important and repeated one.

As previously stated, lists specify individual QCs without a theoretical framework relating them. For instance, Levitin and Redman [18] specify fourteen QCs and explain them based on examples in database management. Lee [11] specify seven QCs based on experiences derived from model development in the manufacturing sector. Moody and Shanks [17] specify eight QCs in a separate list, which they apply in field and laboratory experiments. All three lists have practical relevance. We observed that they overlap in nine of the QCs mentioned in their lists. Some of them even have the same name or concept such as complete [11], completeness [17] and comprehensiveness [18]. Meanwhile others are unique, such as relevance or naturalness in the case of Levitin and Redman [18] and integrity or correctness in the case of Moody and Shanks [17].

In addition, some articles define metrics to measure IM quality, aiming to introduce more objectivity into the evaluation process. For instance, Moody [23] propose twenty-nine metrics mapped to their eight QCs. However, the study revealed that many metrics are very time-consuming to record and only have a marginal benefit for the goal of model improvement. Therefore, we do not include these quality metrics in Table 1.

Overall, the sets of QCs defined within theoretical frameworks are abstract. The sets of QCs defined in lists are more specific and thus more useful for practical application [24].

Table 1. Overview of conceptual model quality.

Reference	Represent.	Quality characteristics(QCs)[a]
Lindland, Sindre, Solvberg [19]	and Framework	syntactic correctness, feasible validity, feasible completeness, feasible comprehension
Krogstie [21]	Framework	physical quality, empirical quality, syntactic quality, semantic quality, perceived semantic quality, pragmatic quality, social quality, deontic quality
Nelson et al. [20]	Framework	syntactic quality, semantic quality, intensional quality, empirical quality, applied domain knowledge quality, applied model knowledge quality, applied language knowledge quality
Levitin and Redman [18]	List	relevance, unambiguous definitions, obtainability of values, comprehensiveness, essentialness, attribute granularity, domain precision, naturalness, occurrence identifiability, homogeneity, semantic consistency, structural consistency, robustness, flexibility
Lee [11]	List	complete, sharable, stable, extensible, well-structured, precise, unambiguous
Moody and Shanks [17]	List	integration, simplicity, completeness, understandability, flexibility, implementability, correctness, integrity

[a] Full details are available in the provided references.

4.2 Conceptual Quality Frameworks

Model developers can evaluate IMs against QCs using the different conceptual quality frameworks available in the literature. In Table 2, we list these frameworks and divide them into two groups: theory-driven evaluation frameworks and practice-driven evaluation frameworks.

The framework proposed by Lindland, Sindre, and Solvberg [19] aims to identify QCs referred to as quality goals and means for achieving them. It applies to conceptual models and the modelling process. Krogstie [21] extend this framework, considering semiotic theory. It also distinguishes between goals and means and applies to the quality of models and modelling languages. Nelson et al. [20] also builds on the framework of Sindre, and Solvberg [19] and combines it with an ontological model by Wand and Weber [22]. It applies to the evaluation of conceptual models and the modelling process. All these frameworks are theory-driven.

Moody and Shanks [25] propose a framework for the evaluation and improvement of IMs (according to our IM definition in Sect. 2). Authors in Moody and Shanks [17] and Moody [23] present a refined version of this framework. Similar to the goals and means described by Lindland, Sindre, and Solvberg [19] and Krogstie [21], also Moody and Shanks [17] and Moody [23] distinguish the quality factors from the improvement strategy. In contrast to the framework proposed by Lindland, Sindre, and Solvberg [19], the constructs quality factors, stakeholders, quality metrics, quality review, quality issue, and improvement strategy defined by Moody [23] and Moody and Shanks [17] emphasise the practical orientation. This framework is practice-driven.

Finally, Shanks and Darke [24] build upon the theory-driven [26] and the practice-driven [25] frameworks to analyse their mutual influence.

Overall, all frameworks make contributions towards understanding the quality of conceptual models. Most distinguish between goals and means. However, only one framework addressed its practical application. In addition, what remains lacking is a framework that provides a structured guiding process for evaluating these models.

Table 2. Overview of conceptual quality frameworks.

Reference	Framework applicability	Approach[a]
Lindland, Sindre, and Solvberg [19]	Identifying quality-improvement goals and means to achieve them for conceptual models and the modelling process	TD
Krogstie [21]	Evaluating quality of models and modelling languages	TD
Nelson et al. [20]	Evaluating conceptual models and the modelling process	TD
Moody and Shanks [17]	Evaluation and improvement of IMs	PD
Shanks and Darke [24]	Understanding and evaluating quality in conceptual models	PD/TD

[a]TD being theory-driven; PD being practice-driven.

5 Discussion

Based on our narrative literature review, we observed that most literature emerged in the 1990s and early 2000s following the rise of information systems [2]. Recently, these approaches have gained renewed attention due to a push in digitalisation processes across sectors [27,28]. Although we followed a structured protocol for our narrative literature search, the number of results may vary compared to other literature review methods. Additionally, our focus is primarily on academic literature. The inclusion of grey literature, such as standards or domain-specific reports, could offer additional valuable insights into the evaluation of new IMs and DMs.

We generated a simple visual illustration mapping the focus of either IM approaches or DM approaches to existing ones in literature. Although we found several approaches for IMs, we did not for DMs. The reason for such a finding might lie in our specific separation between IMs & DMs. Yet, it might be an opportunity to develop a specific or a combined evaluation approach defining steps.

Although DMs are based on previously defined IMs, their evaluation is still essential. It is important to verify whether the specifications of the DM have been implemented correctly. This includes not only verifying whether the defined entities and attributes are fully included in the DM, but also whether implementation-relevant information, such as data types, matches the conceptual definition in the IM or their correct implementation. In the case of informally formulated IMs, the evaluation effort might be greater, as e.g., correct name structures in the DM must additionally be verified.

Combined evaluation methods for IMs & DMs might reduce the evaluation effort of separate evaluations. On the one hand, depending on the model's complexity, a single evaluation session may be sufficient for both model types. On the other hand, if IMs & DMs share similar QCs, it might not be necessary to evaluate both model types against all QCs. For example, if the IM has been successfully evaluated against the QC *naturalness* [18], we can assume that the DM remains unaffected in this respect, as it primarily adds implementation-specific information.

Since current evaluation approaches stay at a high level and lack structured guidance, new evaluation methods, either for DMs or in combination with IMs, should focus on defining clear and actionable steps to support model developers in the evaluation of new IMs & DMs.

In summary, we provide a simple overview of existing approaches for model developers to evaluate new IMs & DMs and highlights the need for future research in the design of evaluation methods.

6 Conclusion

Service interaction depends on correct information exchanges, which require the evaluation of IMs & DMs. We conducted a narrative literature review of academic articles following a structured search and analysis protocol to understand the current status of IM & DM evaluation approaches. Based on the analysed literature, we have generated a simple visual illustration to support model developers in identifying the appropriate approaches for evaluating their new IMs & DMs. The literature review revealed a gap in approaches to DMs evaluation. Our findings suggest that future research should focus on the design of a structured evaluation method that considers both IM & DM characteristics. By providing model developers with better support for ex-ante evaluations during their design process of new IMs & DMs, we can contribute to efficient and effective service interactions.

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Tanned-ReLU: A Bounded and Smooth Activation Function for Reliable Deep Learning on Chaotic Multi-variate Data

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Abstract. In real-world applications of Deep Learning (DL), where multi-variate data is most prominently processed, the choice of Activation Function (AF) plays a critical role for reliable generalization and good convergence. Traditional AFs such as Rectified Linear Unit (ReLU) and its advanced variants such as Leaky-ReLU (L-ReLU), and Parametric-ReLU (P-ReLU) are most commonly used due to their simplicity and effectiveness. However, these functions are inherently unbounded and non-smooth, which can lead to unstable gradients with unoptimized convergence and therefore poor generalization, particularly when processing chaotic, large magnitude floating point values. Additionally, extreme values combined with steep slopes can trigger chain reaction of overcompensation, further destabilizing the learning process. To address these issues, while retaining the simplicity of the widely as-default preferred ReLU AF and its derivatives, we propose Tanned-ReLU (Td-ReLU), a novel AF for artificial neural networks that combines the hyperbolic tangent (*tanh*) and ReLU for smooth and bounded outputs for volatile inputs. The proposed AF is evaluated on a diverse set of real-world multivariate datasets with high relevance to business critical decision making domain, including 5G Quality of Service, wind power forecasting, and IoT based water quality monitoring. Using DL models such as Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) models, Td-ReLU consistently outperformed state-of-the-art ReLU and its counterparts (L-ReLU and P-ReLU); with substantial improvements in Relative Root Mean Squared Error (RRMSE), showing reductions of up to 82.44% compared to P-ReLU, up to 5.18% compared to L-ReLU, and up to 1.07% compared to ReLU across said datasets. These results underline Td-ReLU's consistency and generalization ability, confirming it as a strong alternative to traditional activation functions for applications involving complex temporal and multivariate data, qualities that are highly valuable in enterprise scale DL systems for deployment and decision making.

Keywords: Tanned-ReLU · Td-ReLU

1 Introduction

This research contributes to the field of Deep Learning (DL), particularly for enterprise-level use cases where data is often multivariate, volatile, and associated with regression tasks. Neural Network (NN), an architecture that has enabled computational intelligence,

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are rooted in decades of theoretical advancements in the field of statistics and probability, and in their translation into problems that require a probabilistic approach to be solved. The demand for NNs, especially in their more complex DL form, has increased with the digital age, especially after the internet revolution, where large data handling has been the bottleneck for utilizing the NNs to fully realize their abilities. Therefore, building upon the foundational developments outlined in [1], the past 30 years have since focused mainly on the development in supporting areas such as large-scale data collection and preprocessing/ cleaning, storage solutions, compute power and decentralized computing, accessibility to machine learning models, and telecommunications for sustainable deployment. The maturity in abovementioned has empowered to set off a chain reaction of novel and revolutionary architectures in the field of DL (e.g. Generative Adversarial Networks, Transformers etc.). At the heart of the DL domain lies the activation function, a seemingly simple component that governs gradient flow, and influences the convergence behavior during training by introducing non-linearity into NN for capturing complex data patterns [2]. Its design choice can significantly influence a model's generalization ability and determine its suitability for deployment [2].

There are several common AFs, including step, sigmoid, *tanh*, and Rectified Linear Unit (ReLU), each with distinct properties for transforming inputs [2]. ReLU; being widely utilized and as a rule-of-thumb a default choice, being more efficient than other traditional AFs (*tanh*, sigmoid, binary-step etc.) [3]; has led to further variants such as Leaky-ReLU (L-ReLU) and Parametric-ReLU (P-ReLU), which address the "Dying ReLU" problem, where neurons stop learning due to zero gradients for negative inputs [3]. However, the problem of non-bounded large, positive values and potentially large step increments can lead to poor prediction results [4]. Hence, this study focuses on mitigating these issues by presenting a novel AF method and exploring the advantages of its smooth gradient, bounded and non-linear nature due to the hyperbolic tangent being embedded with the ReLU AF.

A similar study took place in [5], where Dynamic-ReLU AF was devised (sigmoid + ReLU). One of the shortcomings of Sigmoid AF is that it is non-zero-centered and causes bias towards positive side [6]. The upper bound of gradient of *tanh* is 1, which is four times that of Sigmoid (0.25), resulting in the former AF achieving convergence faster [6]. Therefore, due to clear advantages of *tanh* over Sigmoid, this paper focuses on using and exploring *tanh* based ReLU solution to overcome the inherent disadvantages of the Sigmoid.

The key contributions of this work are:

- Introducing Td-ReLU and its theoretical significance.
- Comparison of Td-ReLU against ReLU, P-ReLU, and L-ReLU using three highly diverse multivariate regression datasets: wind power generation (a business-critical task for utility companies in forecasting energy potential), water quality monitoring via Biochemical Oxygen Demand (BOD), and 5G resource allocation (a key factor in assessing user satisfaction based on Quality of Service, QoS). The evaluation employs various deep learning (DL) models to comprehensively assess the practical performance and applicability of the activation functions under study.

The rest of the paper is organized as follows: Sect. 2 covers the datasets, preprocessing, DL model configurations, Td-ReLU architecture, and evaluation metrics. Section 3 presents the results and their interpretation. Section 4 concludes with findings and future directions.

2 Methodology

Herein, we first introduce the architecture and theoretical background of Td-ReLU in Sub-Sect. 2.1. The research approach is presented in Sub-Sect. 2.2. The details pertaining to datasets and DL models' configurations utilized are covered in Sub-Sect. 2.3, and 2.4, respectively.

2.1 Tanned-ReLU and Its Theoretical Background

Being an AF, Td-ReLU is part of the fundamental architecture of NN. It is derived by applying the hyperbolic tangent (*tanh*) on the ReLU (Eq. 1) AF's output, as shown in Eq. 2.

$$ReLU(x) = \max(0, x) \tag{1}$$

$$Tanned{-}ReLU(x) = tanh(ReLU(x)) \tag{2}$$

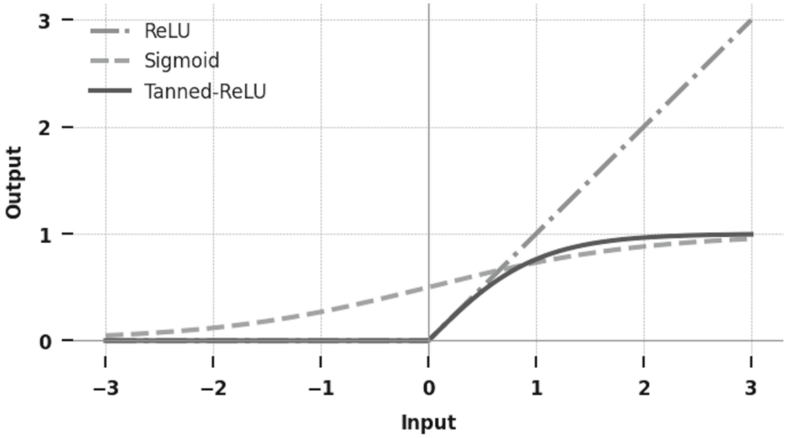
where x is the input numerical value. For comparison, the L-ReLU [7], given in Eq. 3, outputs the same input x when x is zero or a positive number. However, for a negative input value, a near-to-zero constant multiplier a (typically 0.01 or 0.001) is introduced to offer the capability to consider the effect of negative numbers of the data.

$$Leaky{-}ReLU(x) = \begin{cases} x \;\; if \; x \geq 0 \\ ax \; if \; x < 0 \end{cases} \tag{3}$$

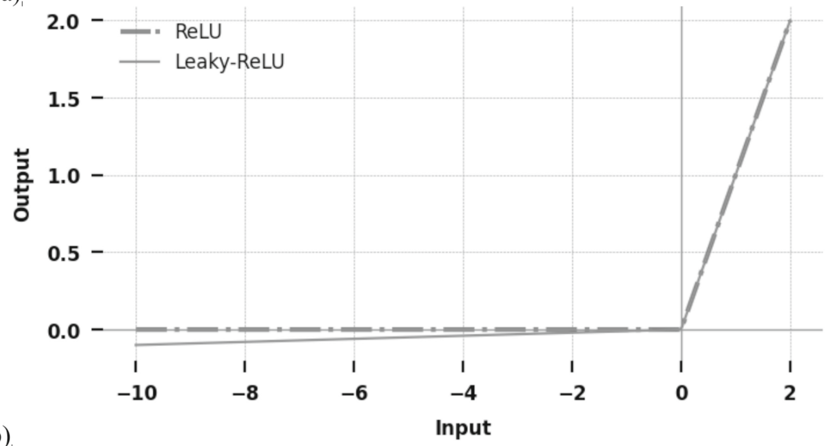
The disadvantage of L-ReLU over its advantage of remaining a simple architecture, is that it uses a constant value of a. In contrast, P-ReLU [8] extends L-ReLU by allowing the a parameter to be learnable during training. This makes P-ReLU more adaptive, as the negative slope is dynamically adjusted based on the data, potentially improving model performance; albeit at the cost of increased computational complexity.

Figure 1(a) illustrates a comparison between the output behavior of ReLU and Td-ReLU across a given input range. To preempt a potential source of confusion, the sigmoid function is also plotted for reference. While both Td-ReLU and the sigmoid function produce outputs in the range of 0 to 1, their characteristics differ significantly. The sigmoid function transforms both positive and negative inputs into a bounded output between 0 and 1. In contrast, Td-ReLU, like ReLU, discards negative inputs entirely and applies the hyperbolic tangent only to the non-negative part, resulting in a different output curve.

An intuitive way to explain the significance of Td-ReLU over ReLU is the introduction of non-linearity and smooth gradients. ReLU discards negative values making it simple in computation but the problem of its linear nature, where it outputs exactly its unbounded positive inputs, can be mitigated if non-linear and bounded approach is used



a)



b)

Fig. 1. Visual representation of activation functions a) Comparison of ReLU, Sigmoid, and Tanned-ReLU activation functions; b) Illustration of the behavioral difference between ReLU and Leaky-ReLU.

[4]. For this purpose, a smooth gradient via *tanh* calculation insures that for small input changes, there are predictable and small changes in output. Hence, catalyzing the neurons in convergence to correct predictions [9]. In contrast, the ReLU's nature of linear output for an input exposes NN to sharp transitions. Moreover, non-linearity enhances the ability to infer complex patterns [9]. These activation functions serve as alternatives to one another, with each offering advantages for specific use cases that depends on abstract nature of various datasets. Therefore, multiple independent multivariate datasets of both high and low CVs has been utilized for testing the said AFs' efficacy comprehensively.

Figure 1(b) presents the visual difference between the output of L-ReLU and ReLU for a given input. Note that Parametric ReLU (P-ReLU) shares the same functional structure as L-ReLU, with the key distinction that the negative slope multiplier *a* in P-ReLU is not fixed but learnable. This learnable parameter allows the slope of the negative region to adapt during training, resulting in a dynamic adjustment of the output curve based on the data.

2.2 Research Approach

This research follows the principles of empirical evaluation in machine learning [10]; which involves multiple practical datasets utilization, independent implementation and comparison of the subject model versus state-of-the-art counterparts, and application of multiple evaluation metrics to conclude the effectiveness of the subject.

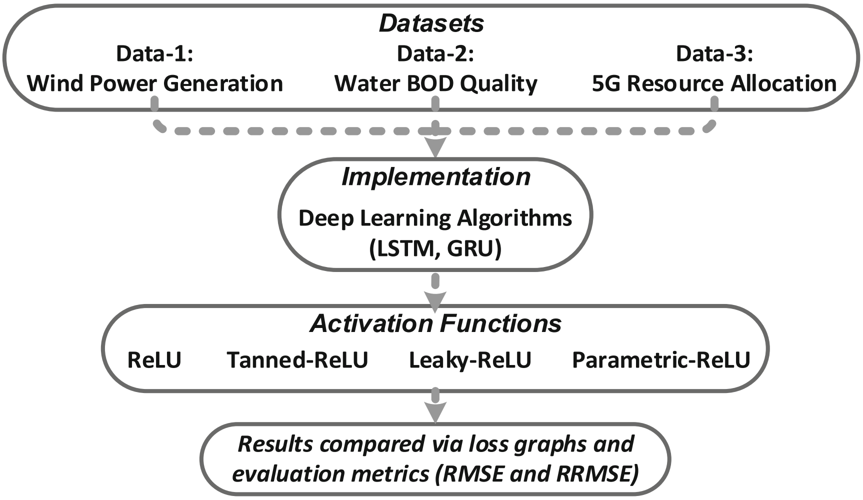


Fig. 2. Proposed holistic view of the subject research's approach

To evaluate the efficacy of Td-ReLU, three datasets are selected to present an adequate challenge to the subject AF. The datasets are diverse, multivariate, and chaotic in nature. Given their long sequenced regression type, the DL models that benefits from memory for extended sequences are utilized (specifically; Gated Recurrent Unit or GRU, Long Short-Term Memory or LSTM). Then, while holding the model configuration and experimental setup consistent for each dataset, the AFs are varied to enable independent comparison. The results are not only evaluated via the popular industry-standard metric Root Mean Squared Error (RMSE) [11] and intuitive percentage based Relative Root Mean Squared Error (RRMSE), but also via loss graphs that gives a visible insight into training stability, in contrast to the pure numeric comparisons. Figure 2 gives an overview of the approach of research for evaluating the effectiveness of subject AF.

2.3 Datasets Employed

The following is an introduction to the three datasets used in this study, hereafter referred to as Data-1, Data-2, and Data-3 for convenience.

Data-1 refers to Wind power generation data, has been acquired from the Foundation Wind Energy Limited-I (FWEL-I) site present in District Thatta, Pakistan. It is a 5 year, hourly period data set with 1908 data points from 10th April, 2015 to 29th, June, 2020. Input features utilized are wind velocity (meters per second or m/s), wind direction (0 to 360°), temperature (degrees Celsius or °C), humidity (relative humidity %), and pressure (hectopascals or hPa). The label for output is power generated in kilowatt (kW). The dataset was requested and acquired from the FWEL company [12].

Data-2 consists of Water BOD (Biochemical Oxygen Demand) quality measurements, which is a key indicator of water pollution. The dataset includes 1000 steps of Input features including temperature (°C), pH value and Dissolved Oxygen (DO) which effects the outcome of BOD output label column. The dataset was utilized from [13]; however, the missing data points have been imputed using the Mean Imputation method for subsequent use in the Machine Learning (ML) workflow.

Data-3 pertains to 5G resource allocation. This dataset is an insight towards how a 5G network manages resource allocation across various applications and user demands. The dataset includes 400 steps of Input features such as, Application Type (Background download, Video call, Streaming, Online gaming, Emergency service, IOT (Internet of Things) temperature, File download, Voice call, VoIP Call, Web browsing); Signal strength (dBm or decibel-milliwatts); Latency (milliseconds or ms); Required Bandwidth (Megabits per second or Mbps); Allocated Bandwidth (Mbps); and the label column of Resource Allocation (%) out of the total bandwidth available to the system. The source of the dataset can be found at [14].

To contextualize the datasets, average Coefficient of Variation (CV) was computed per dataset, yielding 57.29% (Data-1), 6.39% (Data-2), and 59.92% (Data-3). Data-2's low CV indicates stability, while the higher CVs of Data-1 and Data-3 reflect greater variability, enabling evaluation of Td-ReLU under both stable and volatile conditions.

2.4 DL Models, Configurations, and Evaluation Metrics

The study utilized two well-established DL models, the GRU and LSTM [15, 16], to predict outcomes in our datasets and consequently compare the performance of Td-ReLU and its counterparts when applied across various datasets. Various configurations of NNs were employed by using techniques such as stacking [17], cross-validation [18], and dropout [19] to enhance model performance and generalization. The Table 1 shows best performing configuration of models used on each dataset, determined through repeated testing. The performance is evaluated using RMSE [10]. Additionally, for intuitive interpretation of results in loss percentages, the RRMSE is employed [20].

3 Numerical Experimentations

In this section, implementation wise results are covered with respect to each of the dataset utilized as the use-case for performance evaluation of the discussed configurations of DL models in Table 1. The comparison of ReLU and Tanned-ReLU in context of evaluation metrics of RMSE and RRMSE is the focus in this section. Additionally, insight into model performance while training, specifically, the model loss graphs (training loss vs validation loss) are also provided.

Table 1. Configuration parameters used for subject datasets.

Dataset	Configuration
Data-1	3-layer stacked with 100 LSTM cells each, 3 times Cross Validation, 0.1 Dropout, Train-Test split (0.8: 0.2)
Data-2	3-layer stacked (LSTM 200-LSTM 200-GRU 100 cells), 0.1 Dropout, Train-Test split (0.8: 0.2)
Data-3	4-layer stacked (GRU 200-GRU 100-GRU 50-GRU 25-Dense 5), 5 times Cross Validation, 0.1 Dropout, Train-Test split (0.8: 0.2)

Utilizing Data-1, the results obtained using DL models are presented in Fig. 3. With 100 epochs applied, all the AFs', except P-ReLU, training and validation loss lines converge within the first few epochs and remains consistently in-line with each other, close to zero at the end of the epoch range. This indicates the DL model is learning without overfitting, and is able to generalize the patterns of the given dataset. In case of P-ReLU, the Validation loss is less than Training loss and compared to other AFs loss graphs, it is not closer to zero. This indicates underfitting performance, where the model is not able to learn from patterns meaningfully.

Utilizing Data-2, Fig. 4 shows that all AFs exhibit satisfactory convergence, with training and validation losses closely aligned and approaching zero. In Fig. 5 for Data-3, the AFs struggle up to the 37th epoch. After that, the validation and training loss lines align and smoothly approach zero by the final epoch. However, the P-ReLU shows a slight but noticeable chaotic dip at the end, indicating worse performance than the other AFs.

The RMSE and RRMSE obtained, is illustrated in Fig. 6 against the subject AFs for all the datasets. Utilizing Data-1, the RMSE show identical values for subject AFs, indicating a similar overall error magnitude, except for the P-ReLU AF which performs much worse. Looking at the RRMSE, which provides a normalized measure of error in percentages for better intuition, reveals 8.77% percent error, which is lowest compared to the 9.63% and 10.03% RRMSE for L-ReLU and ReLU AFs. A high 91.21% RRMSE was observed for P-ReLU, notably due to the data's steep, intermittent nature causing the sensitive learnable a multiplier used in P-ReLU to be effected negatively from the steep negative momentum of the chaotic data points. This result is testament to the fact that the dataset selected for this study is able to stress test the subject AFs. It also highlights Td-ReLU's promising performance compared to state-of-the-art approaches.

Pertinent to Data-2, all AFs exhibit closely grouped RRMSE values ranging from 7.38% to 8.39%, indicating consistent performance. Td-ReLU with 7.50% RRMSE outperforms P-ReLU and ReLU, while this time L-ReLU has the lowest RRMSE at 7.38%. RMSE values also remain similar across all AFs (range between 0.05 and 0.057 observed), showing minimal absolute error variation.

For Data-3, the lowest RMSE value of 0.014 is observed for Td-ReLU, while higher values of 0.13, 0.021, and 0.14 observed for L-ReLU, ReLU, and P-ReLU, respectively. Examining RRMSE, Td-ReLU achieves the lowest value at 21.29%, followed by ReLU and L-ReLU at 22.36% and 26.47%, respectively. P-ReLU, on the other hand, reaches

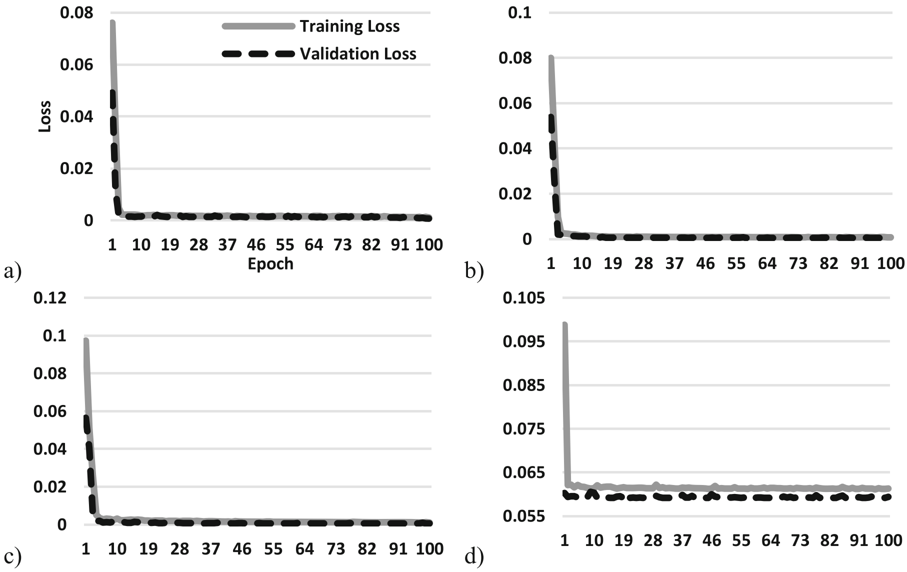


Fig. 3. Loss graph results for the implementation of (a) ReLU (b) Td-ReLU (c) L-ReLU (d) P-ReLU for Data-1.

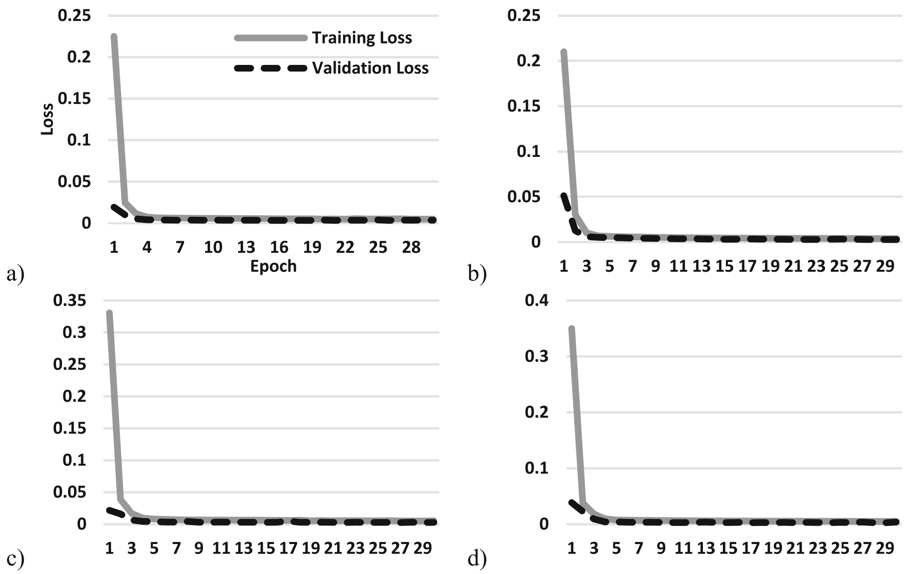


Fig. 4. Loss graph results for the implementation of (a) ReLU (b) Td-ReLU (c) L-ReLU (d) P-ReLU for Data-2.

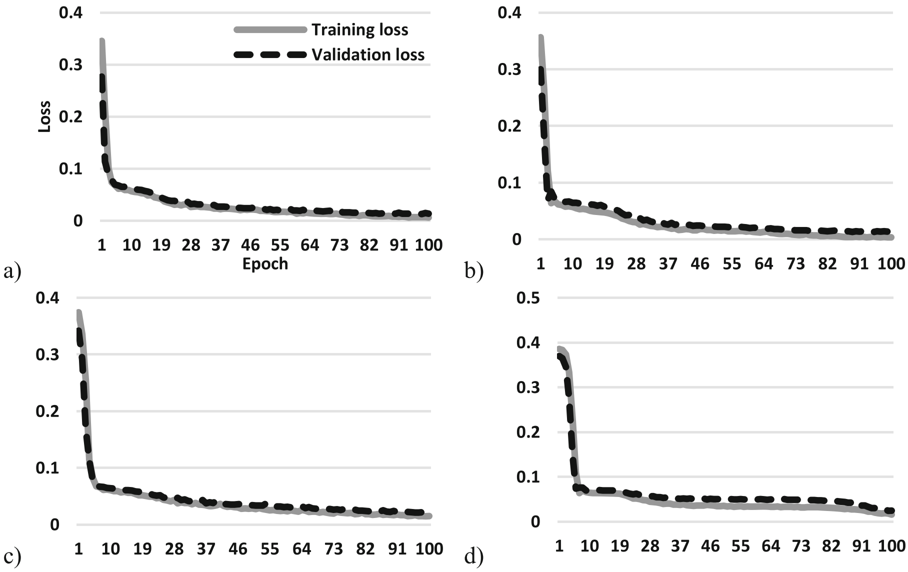


Fig. 5. Loss graph results for the implementation of (a) ReLU (b) Td-ReLU (c) L-ReLU (d) P-ReLU for Data-3.

the highest RRMSE at 29.78%, reinforcing its sensitivity to the dataset's intermittent structure. The L-ReLU which performed slightly better than Td-ReLU for Data-2 struggles with this dataset due to steep negative momentum slopes present, further supporting the stable performance by Td-ReLU in a data of chaotic, intermittent nature.

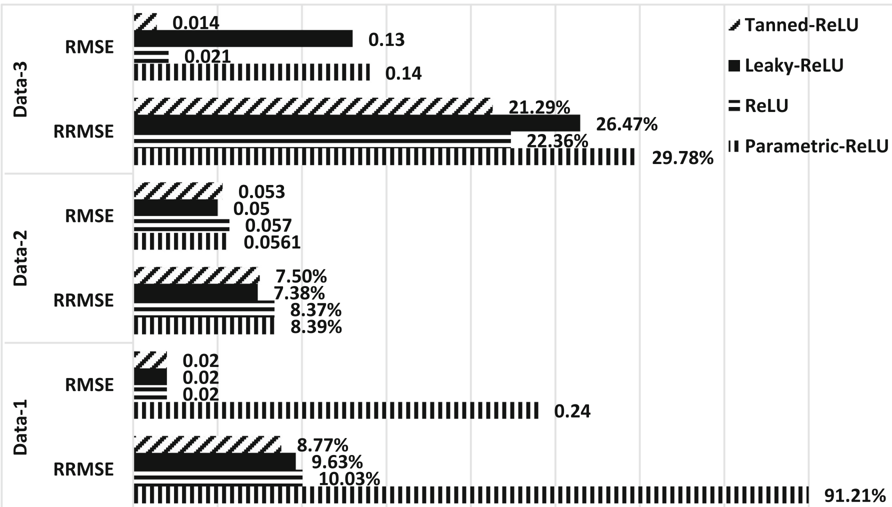


Fig. 6. Comparison of RRMSE and RMSE for Td-ReLU, L-ReLU, ReLU, and P-ReLU AFs applied to the three subject datasets (lower is better).

4 Conclusion

This paper presents Td-ReLU, a novel activation function that extends the traditional ReLU by integrating properties of the hyperbolic tangent to produce smoother gradient transitions and bounded outputs in the range (0, 1). Unlike existing ReLU based functions (such as L-ReLU and P-ReLU), which remain unbounded and non-smooth, Td-ReLU's wave function improves convergence and training stability in the presence of complex and volatile data.

When stress-tested on three practical multivariate datasets, Td-ReLU achieved lower RRMSE values compared to the much more sophisticated state-of-the-art P-ReLU, demonstrating substantial enhancements, with RRMSE reductions of 82.44% for Data-1, 0.89% for Data-2, and 8.49% for Data-3. In context of ReLU, the Td-ReLU implementation resulted in improvements of 1.26% on Data-1, 0.87% on Data-2, and 1.07% on Data-3. Additionally, Td-ReLU outperformed L-ReLU, showing RRMSE improvements of 0.86% on Data-1 and 5.18% on Data-3. These findings underscore the stability of Td-ReLU and its efficacy in enabling improved model convergence and generalization. Such reliability and performance gains are particularly valuable in enterprise environments, where predictive accuracy and robustness directly influence strategic, operational, and real-time decision-making, as in power forecasting for utility companies (Data-1), or resource optimization for wireless service providers (Data-3).

Future research is encouraged to explore Td-ReLU's effectiveness in broader domains such as computer vision, since being an AF, the Td-ReLU is directly integratable to other DL models like CNN (Convolution NN).

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Open Data Portals Engagement: A Cross-Country Analysis of Game Elements

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Abstract. Despite their pivotal role in promoting transparency, open data portals often struggle to engage citizens, functioning instead as static 'data graveyards'. While external activities, such as hackathons, can raise awareness, they do not directly cultivate sustained engagement within the portals. One promising approach to leverage citizens' engagement motivation is the integration of game elements to transform passive data access into interactive gamified experiences. However, despite its potential, there is limited research on gamified citizens' motivation to engage with open data portals. This paper examines how static and dynamic game elements are implemented across 31 open data portals. Lastly, we use the Self-Concordance Model to discuss the alignment between motivation, personal values, and game elements. Our findings reveal that most portals incorporate 'discovery' elements into their dataset-searching features, subtly gamifying exploration. Additionally, portals emphasising external activities, such as hackathons and events, often lack integrated social features, suggesting a trade-off between external engagement and sustained in-portal interaction. These findings challenge the assumption that open data engagement relies primarily on external initiatives, emphasising in-portal gamification instead. This study provides recommendations for policymakers to engage with users within open data portals.

Keywords: Open Data Portals · Gamification · Game Elements · In-Portal Engagement · Cross-Country Analysis · Self-Concordance Model

1 Introduction

Open data portals have enhanced transparency and drive innovation by increasing citizens' access to data [1]. However, they frequently fail to engage citizens, let alone make an impact [2]. Studies reveal risks that portals may operate as data graveyards, where datasets are published but rarely reused or discussed [3, 4]. Governments often rely on external activities, such as hackathons or data challenges [5], to increase open data engagement. Yet, these initiatives are costly [6], episodic [7], and exclusionary: they primarily attract highly skilled citizens, such as developers and data scientists, leaving non-expert citizens behind [8]. While hackathons generate short-term innovation, they often do not maintain sustained outcomes [9], especially for interaction within portals. There is a need to examine citizens' engagement motivation and alternatives to leverage them.

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Gamification, integrating game elements into the portals [10], offers a promising alternative by leveraging personal motivation. Despite the open data portals' gamification potential to transform interactions into enjoyable experiences, it remains underexplored. Recent studies focus on gamification in digital platforms [11], while not analysing the game elements in open data portals' context [12].

The lack of research on connecting citizens' motivation with game elements in open data portals highlights the need to examine the current implementation of game elements that engage citizens with open data portals. This paper addresses the issue by conducting the first cross-country gamification analysis, comparing and contrasting the implementation of game elements in the existing open data portals, and examining how each game element can be designed to engage citizens, conceptualised using motivation theory that relates to the personal value [13].

The paper proceeds as follows: Sect. 2 provides background on citizens' motivation and gamified open data portals. Section 3 outlines the research methodology. Section 4 presents the results. Section 5 discusses the findings. Section 6 concludes with recommendations.

2 Background

In this section, we provide an overview of the current engagement landscape of open data portals. We then conceptualise the citizens' motivation to engage with open data portals. Finally, we outline the game elements identified in the literature based on our prior study.

2.1 Open Data Portals' Engagement and Self-concordance Model

Open data portals emerged as part of global open government initiatives, which involve making governments' data publicly available [14]. However, despite their potential, open data portals face significant hurdles. Citizens' engagement in open data portals remains low, with studies noting that non-citizens outnumber datasets relevant to citizens [15]. Short-term initiatives, such as hackathons or events, while popular, often fail to sustain engagement beyond highly skilled individuals [5]. These engagement issues emphasise the need to examine citizens' motivation to engage with open data portals.

In this paper, we adopt the Self-Concordance Model (SCM) to conceptualise citizens' motivation to engage with open data portals. We chose SCM over other frameworks because it directly addresses different types of citizens' motivation, which was crucial for engaging open data portals [16] and digital platforms [17].

SCM addresses citizens' personal motivation: external, introjected, identified, and intrinsic [13]. External motivation stems from external rewards or consequences. Introjected motivation arises from an internalised sense of obligation to maintain a positive self-image. Identified motivation occurs when individuals engage because it aligns with their values. Lastly, intrinsic motivation refers to the satisfaction or enjoyment derived from engaging in the activity itself.

2.2 Gamification in Open Data Portals

One way of leveraging citizens' motivations is by using gamification, integrating game elements in non-game contexts [10]. Gamification has emerged as a powerful tool to motivate participation in digital platforms, such as in education and government sectors [18]. Civic tech tools, such as SeeClickFix, gamify civic reporting by publicly acknowledging citizens' contributions, demonstrating the potential of gamification to foster citizens' engagement [19]. While preliminary studies suggest that gamification could incentivise participation [20], its application in open data portals remains scarce [12].

Due to the limited research specifically addressing gamification in open data portals, we adopt a pragmatic approach to broaden the sources of information about gamification within digital governments. This approach builds on our accepted prior work that systematically reviewed 78 studies on gamified citizen engagement in government digital platforms, which identified the taxonomy of static and dynamic game elements and connected them with SCM [11].

In the next section, we outline our methodology for examining open data portals' implementation of game elements.

3 Research Methodology

To investigate the implementation of game elements designed to engage citizens in existing open data portals, we begin by outlining two research questions that shape our study: 1) What game elements engage citizens in existing open data portals? 2) What other engagement strategies are used in open data portals?

To address these questions, we adopt the Design Science Research (DSR) methodology since it combines practical knowledge with theoretical frameworks [21]. In this context, we analyse the game elements implementation of existing portals as "natural experiments" from the practical side, then we link them with citizens' motivation grounded in the Self-Concordance Model [13].

3.1 Open Data Portal's Analysis

We performed a systematic analysis of 31 open data portals selected through stratified sampling from DataPortals.org, representing 22 countries and five regions (North America, Europe, Asia-Pacific, Africa/Middle East, and Latin America), with one municipal open data portal for each region and three international organisations for comparisons (World Bank, UN, Kaggle). We accessed the portals between January and February 2025 and captured screenshots for later analysis. This time-limited experiment was designed with practical considerations in mind: 1) To avoid the labour-intensive task of exhaustively coding gamification elements across numerous open data portals, and 2) To minimise the need for repeated analysis should any updates occur to the portals. Pilot testing confirmed methodological saturation, with no new insights emerging after 25 portals.

For each region, we choose three to six national open data portals representing the country and one local open data portal representing a city. The detailed information can be obtained in the supplementary material. In North America, we chose the USA, Canada, and Mexico, with New York City serving as the local portal. For Europe, we selected the UK, France, Germany, and the Netherlands for national portals, and Amsterdam served as the representative local portal. We included the EU portal to understand integrated data systems across member states. In the Asia-Pacific region, open data portals in India, South Korea, Singapore, Japan, Indonesia, and Australia should reflect the region's diversity, with Jakarta chosen as the local portal. In Africa and the Middle East, Bahrain, Saudi Arabia, Nigeria, Tunisia, and Qatar should represent the region, with Cape Town serving as the local-level open data portal. In Latin America, Brazil, Argentina, Colombia, and Chile open data portals should ensure regional diversity, with Buenos Aires as the local open data portal. From an international perspective, we chose the World Bank and United Nations portals to highlight globally shared governmental data, while Kaggle is selected to reflect private data portals made accessible to the public. These portals provide a comprehensive and representative snapshot of the global landscape of open data portals across various contexts and scales.

To conduct our analysis, we accessed each portal via a standard web browser (Microsoft Edge) and prioritised replicability by mimicking the experience of casual users without creating accounts. We analysed publicly available features, reflecting the experience of anonymous users accessing the portals from the internet. Navigation paths were standardised by exploring homepages, dataset catalogues, and tutorial sections where applicable, as well as testing interactive features such as search filters, dataset downloads, and feedback forms. This approach ensures that the findings capture the engagement opportunities accessible to citizens without specialised access or technical expertise. However, we acknowledge the limitations of our approach, such as the language barriers that required reliance on browser translation tools and the restricted access to features that require user accounts. Additionally, we recognise the temporal dynamics involved, as the portals' features may evolve and change following the audit.

3.2 Game Elements in Open Data Portals

To further analyse the game elements in each portal, we investigated various game elements explored in our prior study [11] as outlined in Table 1. Then, we conducted a comparative analysis to identify similarities and differences across regions and governmental and international portals. This approach enabled us to evaluate how diverse contexts impact gamification elements in the portals.

On the left side of the table, we analyse static game elements such as 'points', 'badges', and 'leaderboards', which remain consistent throughout user interactions. On the right side, we focus on dynamic game elements such as 'aesthetics', 'ease of use', and 'discovery', which evolve based on user engagement and experience.

In the next section, we discuss the findings from examining existing open data portals, focusing on the prevalence of game elements and their variations, and exploring citizens' engagement strategies in these portals.

Table 1. Game elements assessment for each portal based on our prior study [11].

Game element	Assessment (is there any..)	Game element	Assessment (is there any..)
Points	Point-related elements in the portal, such as rates, scores, number of views, and number of downloads	Progress	Visual progress for citizens is displayed in the portals
Badges	Citizens' achievements are shown in the portals, such as reuses	Aesthetics	Style or themes of portals
Leaderboards	Features that show the position of citizens in a competition on the portal	Ease of use	Easy user interface to use the portals
Levels	Ranks of citizens in the portal	Challenges	Information about the difficulties of analysing the data for citizens
Rewards	Rewards/prizes for citizens	Rarity	Rare items in the portal
Punishments	Penalties for citizens in the portal	Competition/Cooperation	Competition or cooperation for citizens in the portal
Avatars	Citizens' image/profile in the portal	Narrative	Story/information about the dataset
Virtual Goods	Goods/items that citizens get from the portal	Feedback	Feedback mechanism within the portal (not to be confused with feedback outside the portal, such as email)
Virtual Currencies	Coin/money that citizens get from the portal	Discovery	Elements for citizens to discover datasets or reuses, such as a search feature
Tutorials	Guidance on how to use the portal or how to analyse the data in the portal	Social interaction	Elements for citizens' interaction within the portal, such as chats/forums

4 Results

To analyse the findings, we structured our results with our approach to address the two research questions. First, we examine the game elements found in open data portals. Then, we explore the engagement strategies employed, whether through game elements or alternative methods.

4.1 Common Game Elements

Our analysis of 31 open data portals revealed widespread but uneven adoption of gamification mechanics, as outlined in Table 2.

Table 2. The prevalence of game elements (n = 31), with detailed information in the supplementary material.

Element	Portals Using (%)	Example
Discovery	100%	search filters, dataset categories
Ease of Use	100%	simple menu, few clicks
Aesthetics	100%	portals' style/theme
Narrative/Story	97%	dataset information, news, blogs
Tutorial	84%	guide, how to use, training
Achievements	58%	showcases, reuses
Points/Scores	55%	rating, stars, # views, # downloads
Feedback	35%	direct feedback per dataset
Avatars	16%	user's picture/avatars
Social Interaction	16%	In-portal comment
Others	<5%	

'Discovery' element, such as dataset searching by filters or categories, is the most common feature in all portals. We also noticed that 'aesthetics' and 'ease of use' are present in all portals. 'Narrative/story' and 'tutorials' are the second and third most common features in 97% and 84% of portals. 'Achievements', such as showcases, reuse, or use cases of datasets, exist in 58% of the portals, and 'points', including the number of views, downloads, or ratings, appear in 55% of the portals. The direct 'feedback' element is available in 35% of the datasets, while 'avatars' for personalizing users and 'social interaction' for interacting with users are present within 16% of the Portals. Other game elements, such as 'competition/cooperation', 'leaderboards', and 'virtual goods', were observed in just under 5% of portals. However, they occur outside the portal, including hackathons. Despite the high adoption of game elements on private international portal (Kaggle), government portals have shown minimal integration.

4.2 Engagement Strategies

Analysis of existing open data portals reveals a high reliance on external gamified activities, such as hackathons, data challenges, and community workshops, to stimulate engagement, often at the expense of fostering meaningful social interaction within the portal. While these external initiatives generate short-term participation, particularly among tech-savvy users, they often fail to cultivate sustained interaction within the portals, as evidenced by a low in-portal 'social interaction' element. For instance, the USA and India portals regularly host hackathons to crowdsource data-driven solutions. Yet, their portals lack built-in features that enable users to collaborate, share insights, or form communities directly within the interface.

Notably, a subset of portals (approximately 16%, as outlined in Table 2) prioritises in-portal social interaction mechanisms, such as discussion forums and message boards, without relying on external activities. For example, Brazil's open data portal integrates user comment sections alongside datasets, enabling citizens to ask questions, share knowledge, or suggest improvements directly. These portals demonstrate that embedding social elements within the portal interface can create self-sustaining engagement ecosystems, reducing reliance on episodic external events.

5 Discussion

Our analysis of 31 open data portals reveals that gamification remains inconsistently implemented. We highlight the dominance of 'discovery' elements, which subtly encourage data exploration, align with citizens' intrinsic motivation. The implementation of 'aesthetics' and 'ease of use' elements in all portals suggests the importance of intuitive user interface design when governments develop the portals. Together with the 'narrative/story' element, found in 97% of portals, they indicate open data portals' design that caters to users with intrinsic (discovery, ease of use, and aesthetics) and identified motivation (narrative/story) to interact with these portals, such as data enthusiasts. These findings align with Hammerschall's observation that intrinsic motivation, supported by dynamic elements, can sustain long-term engagement [22]. However, this reliance on intrinsic motivation may limit the portals' ability to attract new users who lack an initial interest in open data.

The limited presence of 'social interaction', 'avatars, and 'leaderboards' (<16%) within open data portals highlights a missed opportunity to jumpstart and sustain engagement by combining the static game elements of introjected motivation (avatars and leaderboards) and the dynamic game element of intrinsic motivation (social interaction). This is noted by Thiel et al. [23], who underscore the short-term benefits of 'leaderboards' for starting initial engagement. However, they note that relying solely on it may not be enough to sustain long-term engagement. Our findings suggest a different perspective: most open data portals lack static elements to jumpstart engagement, yet they already incorporate dynamic elements that primarily cater to data enthusiasts. This narrow focus likely contributes to the low overall engagement, as these portals primarily appeal to niche segments. To address this, portals could benefit from incorporating static elements, such as 'tutorials', 'avatars, and 'leaderboards', to attract a broader audience while also expanding dynamic features, such as ‘social interaction’, to better connect with diverse citizen groups and sustain their engagement.

Another finding reveals that portals with external gamified activities lack in-portal social interaction, suggesting a trade-off between external engagement and sustained in-portal interaction. This underscores a broader issue: external events often operate in isolation from the portal’s core infrastructure, creating fragmented engagement that does not translate into habitual portal use for citizen engagement.

Despite the regional and sectoral diversity of our review’s stratified sample, a key limitation lies in its underrepresentation of smaller municipal and non-English portals, potentially overlooking localised approaches. Future studies could explore these portals, providing a more comprehensive analysis of gamification implementation across different contexts. Additionally, future studies could also evaluate the effects of gamification on in-portal engagement, such as integrating ‘social interaction’ within the portals. Finally, although we outlined that gamification elements exist in several portals, implementing them requires developing requirements tailored to each portal.

6 Conclusion

This study provides the first cross-country assessment of gamification elements in open data portals, analysing 31 portals across five regions. Our findings reveal that the game elements are widely implemented, particularly about ‘discovery’, ‘ease of use’, ‘aesthetics’, and ‘narrative/story’. These elements align with the principles of the Self-Concordance Model by fostering intrinsic motivation through enhanced control in dataset discovery processes (discovery) and an intuitive user interface (aesthetics and ease of use). They also support identified motivation by tailoring portals’ narrative to resonate with citizens’ values (narrative/story).

However, the combination of game elements designed to foster intrinsic motivation for citizen interaction within the portal (in-portal social interaction) and introjected motivation (avatars and leaderboards) is less prevalent in government portals. Furthermore, portals focusing solely on external engagements, such as hackathons and events, overlook in-portal engagement and may inadvertently undermine citizens’ motivation to interact with others directly through the portals. This gap highlights an opportunity for governments to explore gamification strategies by combining static game elements to initiate citizens’ participation and dynamic game elements to sustain the engagement within the portals.

For policymakers, these insights underscore the potential of gamification to transform open data portals from static repositories into interactive in-portal engagement platforms. Future research should focus on exploring context-specific gamification strategies and expanding in-portal citizen engagement, ensuring that open data portals evolve from data graveyards into engaging, interactive open data engagement.

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Use of AI. During the preparation of this work, the author(s) used Rewrite/Copilot in order to improve readability. After using this tool/service, the author(s) reviewed, edited, made the content their own and validated the outcome as needed, and take(s) full responsibility for the content of the publication.

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Advancing Credit Assessment: A Hybrid Methodology for Importer Crediting

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Abstract. This paper introduces a hybrid credit assessment methodology tailored specifically to the unique financial, informational, and operational challenges faced by importers. Importers operate at the intersection of cross-border financial risk, fluctuating supply chains, and opaque transactional histories - factors that challenge conventional credit models. While banks rely on structured financial records and established credit histories, P2P platforms harness alternative data and decentralized trust mechanisms such a peer feedback and real-time behavioral signals. Rather than merely merging technologies, the proposed approach integrates differing capabilities: institutional data interpretation dynamical risk modeling, and platform-based investor participation. This synthesis enables a more adaptive, inclusive, and context-aware assessment process. Core components include continuous data validation, alternative trade-data integration, machine learning-driven decision support, and modular feedback loops from lender communities. The methodology is evaluated through a structured literature review and illustrative case applications. By focusing on the informational volatility and operational complexity unique to import-driven businesses, this research contributes a targeted solution to a global financing gap - advancing both credit innovation and trade accessibility.

Keywords: Intelligent Credit System · machine learning · crediting importers · P2P lending platform · credit evaluation

1 Introduction

In the context of global trade, importers occupy a strategically complex position: they are both logistical intermediaries and financial risk bearers. Extending credit to importers is not merely a matter of financial analysis – it involves understanding international supply chains, geopolitical volatility, and real-time transaction behavior. Yet, conventional

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credit assessment models, largely developed for domestic and institutionally embedded businesses, often fall short when applied to this domain.

This paper proposes a hybrid credit assessment methodology specifically designed for the crediting of importers - entitles that operate within fluctuating regulatory, logistical, and market environments. Unlike generic borrowers, importers generate and depend on divorce, dynamic, and often cross-border data streams, making them uniquely difficult to evaluate using traditional risk scoring approaches. Our methodology addresses this challenge by integrating business model innovations from peer-to-peer (P2P) lending with the analytical rigor and interpretive depths of traditional banking institutions.

To avoid conflation and improve clarity, we distinctly address three interrelated yet separate dimensions that underpin the proposed approach business model divergence, informational asymmetry, and technological differentiation. First, from a business perspective, P2P platforms and traditional banks operate under fundamentally different paradigms - P2P models emphasize decentralized risk-sharing and community-based vetting, while banks centralize risk assessment under regulated institutional frameworks. Second, their informational approaches diverge: abanks traditionally rely on audited financial statements and static credit histories, whereas P2P platforms often ingest behavioral, transactional, and reputational data in real time. Importantly, data cleaning and interpretation is not a linear preprocessing task but a continuous, embedded capability - and one that differs markedly between institutions and platforms. Third, on the technological front, P2P systems typically leverage agile, cloud-native architectures and machine learning algorithms for adaptive risk modeling, in contrast to banks' often rigid legacy systems optimized for compliance and stability.

The central contribution of this research lies in demonstrating that integrating these divergent elements – without conflating them – can produce a robust, responsive, and importer-specific credit assessment framework. The system we propose is not simply an amalgamation of technologies, but a careful orchestration of complementary capabilities: institutional trust and interpretability on one hand, and dynamic, data-driven responsiveness on the other.

In the sections that follow, we present the conceptual foundations, data architecture, and operational logic of this hybrid methodology. Special attention is given to the crediting context of importers, whose business models and and profiles demand precision, flexibility, and contextual intelligence in equal measure. By addressing informational volatility, business model incompatibility, and technological misalignment as separate but intersecting challenges, this paper aims to advance a more nuanced and effective approach in global commerce.

2 Literature Review

The literature on credit evaluation systems and methodologies encompasses a broad spectrum of research spanning finance, economics, computer science, and related fields. Within this multifaceted domain, several key themes emerge, shedding light on the challenges, opportunities, and advancements in credit assessment practices, particularly within the context of importation.

The advent of artificial intelligence (AI), machine learning (ML), and big data analytics has ushered in a new era of credit evaluation methodologies. Research by Victor

Gomes Helder et al. explores the application of ML algorithms such as random forests and support vector machines in credit scoring, demonstrating their ability to outperform traditional models in terms of accuracy and efficiency [1]. Similarly, studies by Wang et al. [2] and Zhang et al. [3] highlight the potential of deep learning techniques in credit risk assessment, leveraging neural networks to uncover complex patterns and relationships within large datasets.

Within the domain of manufacturing and importation, unique contextual factors shape credit evaluation practices. Research by Chao et al. delves into the challenges of assessing credit risk in supply chain finance, emphasizing the importance of considering interdependencies and vulnerabilities within supply chains [4]. Additionally, studies by Li et al. [5] and Cheng et al. [6] explore credit evaluation frameworks tailored for small and medium-sized enterprises (SMEs) in manufacturing sectors, highlighting the need for nuanced approaches that account for sector-specific dynamics and risk factors.

The integration of alternative data sources beyond traditional financial metrics holds promise for enhancing the accuracy and granularity of credit assessments. Research by Lee et al. examines the use of non-financial data such as social media activity and web browsing behavior in credit scoring, demonstrating their potential to complement traditional data sources and provide additional insights into borrower behavior and creditworthiness [7].

Peer-to-peer lending platforms have emerged as alternative sources of credit, facilitating direct lending relationships between individual borrowers and lenders. Research by Lin et al. explores the dynamics of P2P lending markets, including risk assessment, pricing mechanisms, and the role of social networks in credit evaluation [8].

While much of the existing literature on lending focuses on general-purpose lending frameworks, the credit evaluation of importers introduces a distinct set of challenges that are underexplored. Importers must navigate factors such as cross-border regulations, fluctuating exchange rates, geopolitical instability, supplier risk, and transport uncertainty, that traditional financial indicators alone may not capture.

3 Methodology

The methodology employed in developing an intelligent system for crediting importers of goods encompasses several key stages, each aimed at achieving a comprehensive and effective credit assessment framework. The methodology integrates principles from data science, machine learning, and domain-specific knowledge to ensure robustness, accuracy, and practicality in the credit evaluation process. The life cycle of development process consists of Data Collection and Preparation, Feature Engineering and Selection, Model Development, Evaluation and Validation, Deployment and Integration, Monitoring and Maintenance.

I. Credit evaluation for importers relies on the ongoing collection, validation and interpretation of diverse and evolving datasets. These include structured financial statements, transactional records, market indicators, and unstructured data from supply chains, trade platforms, and digital interactions. Data sources range from institutional repositories and internal banking systems to public datasets and third-party providers, each varying in reliability, format and update frequency. Importantly, data preparation iis not a preliminary task but a continues, embeded process - crucial for maintaining real-time creditworthiness assessments in volatile markets. This involves iterative cleaning, anomaly detection, and context-aware standardization, often performed dynamically as new data flows in. Traditional banks excel at processing standardized, backward-looking financial data; their interpretive strength lies in stability and compliance. In contrast, P2P platforms often operate on alternative and behavioral datasets, requiring different filtering, modeling, and interpretive logics that prioritize speed, diversity, and adaptability. Merging these capabilities - beyond merely integrating their respective technologies - presents a substantial challenge. The hybrid methodology proposed in this paper does not simply combine data pipelines but seeks to synthesize interpretive strengths from both paradigms, enabling a more comprehensive, real- time and context-sensitive assessment of importer creditworthiness.

II. Feature engineering and selection plays a crucial role in transforming raw data into meaningful features that capture relevant information for credit assessment. This involves the creation of new variables, transformation of existing variables, and extraction of key insights from the data. Feature selection techniques, such as statistical tests, correlation analysis, and domain expertise, are then employed to identify the most informative features for predictive modeling.

III. Machine learning algorithms are leveraged to develop predictive models capable of assessing the creditworthiness of manufacturers and importers. Various supervised learning techniques, including classification algorithms such as logistic regression, decision trees, random forests, and gradient boosting machines, are explored to build predictive models based on labeled training data. Model hyperparameters are tuned using techniques such as grid search and cross-validation to optimize performance and generalization.

IV. The performance of the predictive models is evaluated using appropriate metrics such as accuracy, precision, recall, F1-score, and area under the receiver operating characteristic (ROC) curve. Model validation techniques, including holdout validation, cross-validation, and bootstrapping, are employed to assess model robustness and generalization across different datasets and time periods. Additionally, model interpretability techniques, such as feature importance analysis and partial dependence plots, are used to gain insights into the factors driving credit decisions.

V. Once validated, the predictive models are deployed within the intelligent system infrastructure, enabling seamless integration with existing business processes and decision-making workflows. User-friendly interfaces are designed to facilitate interaction with the system, allowing stakeholders to input relevant data, retrieve credit evaluations, and visualize results in an intuitive manner. Integration with external data sources and APIs enables real-time data updates and dynamic model retraining to ensure ongoing accuracy and relevance.

VI. Continuous monitoring and maintenance of the intelligent system are essential to ensure its reliability, performance, and compliance with evolving regulatory requirements. Monitoring mechanisms are established to track model performance, detect anomalies, and trigger retraining or recalibration as needed. Regular audits and reviews are conducted to assess model fairness, transparency, and ethical compliance, addressing concerns related to bias, discrimination, and privacy.

This methodology lays the foundation for advancing credit assessment practices, enhancing risk management capabilities, and fostering trust and transparency within the global marketplace.

4 Hybrid Approach of Decision-Making

Nowadays there are traditional centralized decision-making approach and decentralized decision-making P2P approach.

Traditional approaches to credit evaluation typically involve centralized decision-making processes, wherein financial institutions, such as banks or credit bureaus, assess the creditworthiness of borrowers based on predetermined criteria and standardized models.

Traditional methods heavily rely on historical financial data, such as credit scores, income statements, and payment histories, to gauge the borrower's creditworthiness. These data are often obtained from credit reports and financial statements submitted by the borrower.

Traditional approaches may lack flexibility in accommodating borrowers with limited credit history or unconventional financial profiles. This can result in exclusionary practices that disadvantage certain demographics, such as young individuals or individuals with thin credit files.

The centralized nature of traditional credit evaluation processes can lead to longer processing times, as applications undergo manual review and approval by loan officers or credit analysts. This can introduce delays and inefficiencies, particularly in time-sensitive lending scenarios.

P2P approaches decentralize credit evaluation processes by connecting borrowers directly with individual lenders or investors through online platforms. Instead of relying solely on centralized institutions, credit decisions are often based on peer-to-peer interactions and community feedback.

P2P platforms leverage alternative data sources beyond traditional financial metrics, such as social media profiles, online behavior, and transactional data, to assess the creditworthiness of borrowers. This allows for a more holistic evaluation of the borrower's financial health and repayment capacity.

P2P lending platforms can increase access to credit for underserved populations or individuals with limited access to traditional banking services. By bypassing traditional credit scoring models, P2P approaches may provide opportunities for borrowers with non-traditional credit histories to access financing.

P2P lending platforms often streamline the credit evaluation and approval process, leveraging automated algorithms and machine learning techniques to assess borrower risk and match borrowers with suitable lenders. This can result in faster approval times and expedited funding for borrowers.

Traditional approaches tend to rely on standardized credit scoring models and historical financial data for risk assessment, whereas P2P approaches may incorporate alternative data sources and peer-to-peer feedback for a more comprehensive evaluation.

P2P approaches generally offer faster approval times and streamlined processes compared to traditional approaches, which may involve manual review and longer processing times.

P2P approaches have the potential to increase access to credit for underserved populations or individuals with limited credit history, whereas traditional approaches may be more restrictive in their eligibility criteria.

Traditional approaches are subject to regulatory oversight and compliance requirements imposed by government agencies and financial regulators, whereas P2P platforms may face regulatory challenges and uncertainty due to their relatively novel nature and decentralized structure.

While traditional approaches to credit evaluation offer stability and regulatory oversight, P2P approaches provide flexibility, speed, and potential access to credit for underserved populations. Both approaches have their respective advantages and limitations, and the choice between them may depend on factors such as regulatory environment, borrower demographics, and lending objectives.

The hybrid methodology for crediting importers integrates elements from both traditional approaches and peer-to-peer (P2P) approaches to create a robust and versatile credit evaluation framework. This methodology leverages the strengths of traditional credit assessment methodologies while incorporating innovative features from P2P lending platforms to enhance accuracy, efficiency, and inclusivity in the credit evaluation process.

The proposed methology is explicitly designed to address the multifaceted credit evaluation needs of importers by integrating business logic, informational diversity, and technological adaptability. From a business standpoint, the system distinguishes between institutional lending moldels and peer-based mechanisms, leveraging the former's regulatory depth and the latter's agility in high-variance environments. Informationally, the system processes heterogeneou data types such as structured finacial reports, real-time trade activity, shipping documents, custom records, and peer-contributed risk assessments – each reflecting a different aspect of importer behavior. Data ingestion an interpretation are treated as continuos processes rather than front-loaded tasks, enabling ongoing risk calibration. Technologically, the architecture employs machine learning algorithms and modular APIs to adaptively score creditworthiness as new data streams are integrated. This layered approach ensures that credit assessments are not only current and granular, but also context-sensitive responding to the operational complexity and volatility that characterize global import activities (Fig. 1).

The hybrid methodology begins with a traditional financial analysis, utilizing historical financial data such as credit scores, income statements, and payment histories to assess the creditworthiness of importers. Benchmarking importers' financial performance against industry standards and best practices provides context for evaluating their financial health and risk profile. Adherence to regulatory requirements ensures compliance and mitigates legal risks associated with credit evaluation.

In addition to traditional financial metrics, the hybrid method incorporates alternative data sources such as social media activity, online reviews, and transactional data to supplement credit assessments. Monitoring market trends and economic indicators provides valuable insights into the importers' industry dynamics and overall market

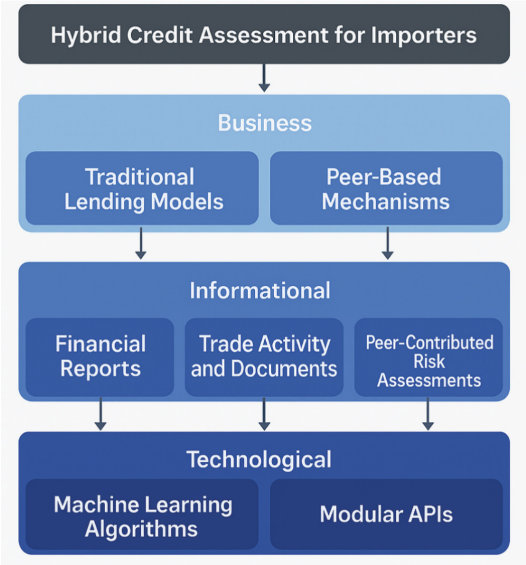

Fig. 1. Hybrid Credit Assessment for Importers

conditions, informing credit decisions. Identifying and analyzing risk indicators such as geopolitical risks, currency fluctuations, and supply chain disruptions enhances the granularity and predictive power of credit assessments.

Introducing elements of peer-to-peer feedback and community-based ratings allows stakeholders, including suppliers, customers, and industry peers, to contribute insights and assessments of importers' creditworthiness. Leveraging real-time data and dynamic risk assessment algorithms enables adaptive credit evaluations that respond to changes in importers' financial circumstances and market conditions. Providing opportunities for investors to participate in funding importers' credit facilities through a P2P lending platform facilitates direct peer-to-peer lending relationships, fostering transparency and accountability in credit transactions.

Employing machine learning algorithms and predictive analytics facilitates automated decision support, enabling importers to receive timely and accurate credit decisions based on comprehensive data analysis. Generating risk scores and credit ratings based on the combined analysis of traditional financial metrics, alternative data sources, and peer feedback provides a standardized framework for evaluating importers' creditworthiness. Ensuring transparency and interpretability in the credit evaluation process through explainable AI techniques allows stakeholders to understand the factors driving credit decisions and identify areas for improvement.

By combining elements from traditional credit assessment methodologies with innovative features from P2P lending platforms, the hybrid method for crediting importers offers a holistic and adaptable approach to credit evaluation. This method enhances the accuracy, efficiency, and inclusivity of credit assessment processes, empowering importers, lenders, and investors to make informed decisions and drive sustainable economic growth.

5 Conclusion

In conclusion, the hybrid method proposed for crediting importers represents a comprehensive and innovative approach to credit evaluation, blending elements from traditional methodologies and peer-to-peer (P2P) lending platforms. By leveraging the strengths of both approaches, this hybrid method offers a versatile framework that enhances the accuracy, efficiency, and inclusivity of credit assessment processes in the importation industry.

Through traditional credit assessment techniques such as financial analysis, industry benchmarking, and regulatory compliance, the hybrid method ensures a robust foundation for evaluating importers' creditworthiness. These established practices provide stability, reliability, and adherence to regulatory standards, instilling confidence in credit decisions.

Moreover, by integrating alternative data sources, market trends analysis, and risk indicators, the hybrid method enhances the granularity and predictive power of credit evaluations. This forward-looking approach enables stakeholders to gain deeper insights into importers' financial health, market positioning, and risk exposure, facilitating more informed and proactive credit decisions.

The incorporation of peer-to-peer features, including community feedback, dynamic risk assessment, and investor participation, further enriches the credit evaluation process. By fostering transparency, accountability, and direct peer-to-peer lending relationships, this aspect of the hybrid method promotes inclusivity, trust, and collaboration within the importation industry.

In practice, the hybrid method offers a flexible and adaptable framework that can be tailored to meet the diverse needs of importers, lenders, and investors across different market segments and geographical regions. Its automated decision support capabilities, powered by predictive modeling and explainable AI, enable stakeholders to navigate complex credit scenarios with confidence and efficiency.

Overall, the hybrid method for crediting importers represents a paradigm shift in credit evaluation practices, driving innovation, resilience, and sustainability in the global importation industry. By embracing the strengths of both traditional and P2P approaches, this method paves the way for a more dynamic, inclusive, and responsive credit ecosystem, fostering economic growth and prosperity for importers and stakeholders alike.

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Aligning Clinical Workflows and AI Integration: Digital Healthcare Reference Model in Dementia and Frailty Care

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Abstract. As healthcare systems face increasing demands from aging populations and the prevalence of neurodegenerative diseases, there is a growing need for integrated, scalable digital solutions. This paper introduces a Digital Healthcare Reference Model (DHRM) developed to enable AI-supported diagnoses for dementia and frailty care. Grounded in Action Research, the model was iteratively constructed through the collaboration of clinical and technical experts. These approaches provided diverse real-world data on clinical workflows, user requirements and care strategies for improving the individuals' well-being and quality of life (QoL). The DHRM formalizes core clinical workflows and defines key actors, data entities and system components, organizing them into a layered architecture that supports data ingestion, processing, decision support, and user interaction. The model bridges clinical practice and technical design, enabling consistent integration of AI-based tools into routine care. By establishing a reusable framework for digital health systems, this work contributes to the development of standardized, explainable and adaptable infrastructures for managing complex, age-related health conditions.

Keywords: Digital Healthcare · Neurodegenerative Diseases · AI-Assisted Clinical Workflows

1 Introduction

The increasing prevalence of neurodegenerative disorders and chronic conditions in aging populations presents significant societal, economic and healthcare challenges [15]. As these demographic shifts lead to a higher incidence of dementia, frailty, and comorbid conditions, traditional healthcare systems face mounting pressure to deliver personalized, long-term care at scale [8]. Recent studies indicate the increasing of dementia prevalence across EU [7,9], while evidence from three (3) large European longitudinal studies focusing on prevalence from age

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group 60–64 onwards through to 80+ suggested that the younger age group (60–64) the smaller prevalence [6,16,17]. While several digital health solutions exist, their integration into routine care remains fragmented due to a lack of unifying frameworks and methodologies that bridge clinical and technical perspectives [5]. A persistent gap exists between domain experts (e.g., healthcare professionals) and technical developers, complicating the translation of medical expertise into system design. However, dementia pathology is present decades before the onset of clinical symptoms and patients with early-onset dementia constitute a significant under-recognized sub-group [11], with latent risks to progress to Mild Cognitive Impairment (MCI) later in life. The latter demonstrates an increasing need on addressing complex and multidimensional health challenges that pose significant burdens on patients and on their families, caregivers, and healthcare systems. Personalization implies a level of precision that seeks to treat the patient as opposed to the disease, taking into account as an example comorbidities, genetic predisposition and environmental factors. Thus, the growing demand for long-term and personalized care highlights the tremendous need for more structured, interoperable, and person-centric approaches in healthcare delivery. While various projects have explored Ambient Assisted Living and smart monitoring systems,—including AI-based analytics and remote monitoring tools— offer new opportunities to support data-driven, patient-centered care strategies. However, there remains a need for a structured, generalizable and unified reference model, and the integration of these technologies into existing clinical pathways. Furthermore, there is a gap in methodological approaches that systematically align clinical and technical perspectives. This paper introduces a Digital Healthcare Reference Model (DHRM) a modular, layered framework for integrating diverse health and care data, aligning clinical practices with AI developments, facilitating the adoption of emerging technologies in the clinical settings, and enabling holistic decision-making processes across divergent care settings. The DHRM is designed with a strong emphasis on meaningful inclusion of patients, caregivers, and families as active participants in the research and care processes, ensuring that their individual needs, values, and preferences are identified, recognized and respected throughout the entire care journey and project lifecycle. Following a comprehensive and co-creative approach the DHRM fosters inclusiveness, participation and the establishment of a human-centered model of care. A key goal of the model is to address the relevant challenge of misalignment between domain knowledge and system development. Our contribution is twofold: (1) the formalization of a reusable reference architecture for digital healthcare systems, and (2) a detailed, real-world use case that demonstrates how co-creation and iterative development can operationalize such a model. The paper is organized as follows. Section 2 reviews related literature on reference models in digital health and AI-supported clinical systems. Section 3 outlines the methodology used to construct the DHRM Model. Section 4 presents the proposed reference model in detail. Section 5 discusses contributions and outlines future work.

2 Related Work

Several studies have contributed to the digital transformation of elderly care, addressing various aspects such as monitoring, decision support, and socio-technical integration. Existing literature highlights key advances and challenges in the digital transformation of elderly care. Almalki et al. [1] propose a framework for Ambient Assisted Living, emphasizing the socio-technical alignment needed for effective technology adoption among older populations. Livingston et al. [11] underscore the importance of early, multi-domain interventions in dementia care, suggesting that personalized care requires coordinated action across clinical domains. Papa et al. [14] explore the role of smart healthcare devices in monitoring wellbeing, demonstrating the feasibility of continuous data collection for personalized interventions through sensor-based monitoring. In parallel, Mans et al. apply [13]process mining techniques to evaluate healthcare workflows, offering methodological tools for extracting and optimizing clinical processes. Recent research increasingly explores the integration of artificial intelligence (AI) in elderly care, particularly for dementia and frailty management [10,12]. While these contributions address critical elements of digital health, they largely focus on specific tools or technologies in isolation and do not offer a generalizable, structured approach to aligning clinical workflows with system design. Our work addresses this methodological gap by proposing a Digital Healthcare Reference Model (DHRM) that formalizes this alignment through a layered architecture co-developed by clinical and technical stakeholders.

3 Methodology

The development of the Digital Healthcare Reference Model followed an iterative, collaborative process and a joint effort involving clinical experts and technical professionals. Clinical partners provided domain-specific knowledge through in-person interviews and a series of Co-Creation Workshops. These workshops focused on identifying care pathways, user needs and practice-level requirements by engaging healthcare professionals, patients and caregivers. In parallel, technical partners contributed system-level constraints, including functional and non-functional requirements, documented through technical meetings and specification work. This effort led to the formulation of a requirements definition document and a reference architecture to support system implementation. Figure 1 illustrates how clinical and technical perspectives were integrated to produce a unified model development trajectory.

To coordinate the modeling activities across these domains, we employed the Action Research (AR) methodology [2], which is particularly suited to settings that require adaptive, real-world feedback during development. Our approach was structured around the AR phases and it was applied repeatedly across the different stages of model construction, producing concrete outputs. AR is well-suited to settings that involve collaboration across disciplinary boundaries, as it provides a process-oriented framework for integrating diverse stakeholder input

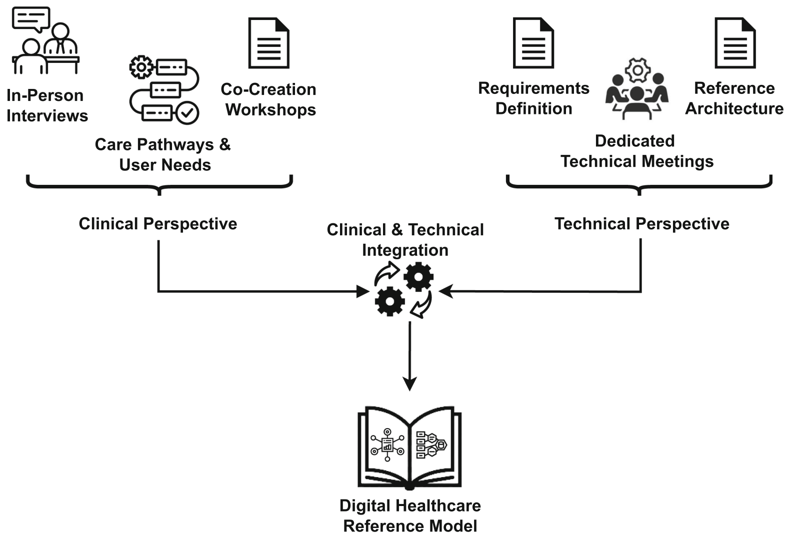

Fig. 1. Integration of Clinical and Technical Aspects in the Development of Digital Healthcare Reference Model.

through iterative cycles of planning, intervention, reflection and adaptation [3,4]. It has been widely applied in contexts where research and system development occur in parallel and where stakeholder engagement plays a central role in shaping both process and output. In our case, AR allowed us to coordinate contributions from clinical professionals, engineers and domain experts and to align them with evolving technical constraints and validation outcomes. We applied all four AR phases—planning, action, iteration and documentation—to each modeling activity, allowing us to progressively refine the model in response to feedback and implementation requirements. Figure 2 illustrates the full AR process applied to our model development. Each phase is shown as a repeatable activity, indicating the iterative refinement of both clinical and technical elements.

We began by defining the conceptual and structural requirements for the DHRM. In line with the planning phase of AR to gather input from clinical and technical contributors through interviews, early technical discussions and analysis of existing system specifications. These sessions surfaced critical information on clinical workflows, regulatory and data constraints and system-level expectations. These inputs help to define the initial scope of the model.

In the action and iteration phases, we then modeled clinical and AI support decision-making workflows, drawing from real implementations. These included diagnostic processes, monitoring routines and therapeutic interventions. Each workflow was mapped to decision-support logic, including AI-assisted operations and validated through review cycles with domain experts. In the next activity, we developed the entity model. This phase aligned with the iteration component of AR. Based on the workflow analysis, we extracted and formalized the key

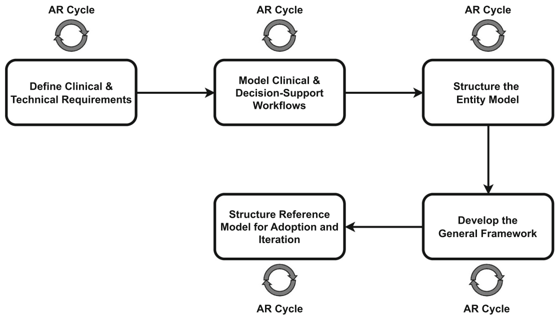

Fig. 2. Iterative development process of the DHRM following the AR methodology.

actors—such as patients, caregivers, clinical assessments, and digital tools—by specifying their attributes and defining how they interact within the healthcare and system contexts. Clinical and technical partners reviewed and refined these definitions to ensure domain fidelity and implementation feasibility. The general framework was constructed by combining the workflows and entities into a layered model. This applied both the action and iteration phases of AR. We defined architectural layers representing clinical services, data processing, decision support and infrastructure. We refined the framework through collaborative review and alignment with integration constraints. This approach not only ensured the relevance and feasibility of the model in real-world settings but also tackled a challenge: the historical misalignment between domain-specific business models (in this case, healthcare workflows) and system-level software design. Finally, we prepared the model for reuse and deployment, applying the documentation and training phase. We formalised the model components as modular units, prepared accompanying descriptions and defined configuration parameters for implementation. We validated alignment with established healthcare interoperability frameworks to support reuse in different deployment environments. Each modeling activity engaged the full AR cycle to ensure the model remained consistent with operational, technical and domain-specific constraints.

4 Digital Healthcare Reference Model

Based on the iterative modeling process described in Sect. 3, we developed the Digital Healthcare Reference Model (DHRM) as the core technical contribution of this work. The DHRM formalizes the alignment between clinical workflows and digital system design, providing a reusable structure for deploying AI-assisted healthcare systems. How described in the Fig. 3 the model comprises two main components: the entity model and the high-level framework. We used the entity model to represent the clinical and technical actors involved in healthcare delivery and we designed the high-level framework to define the architectural layers required for implementation. We built both components based on input from clinical partners, technical contributors and documented system-level requirements. We validated the model structure iteratively. Figure 3 shows the overall structure of the DHRM and the relationship between its components. These components were incrementally developed, validated, and refined through cycles of modeling and feedback. While some elements draw on common healthcare system abstractions, the specific layering, formal entity relationships, and mapping between roles and architectural functions represent the novel contribution of this paper. The model is designed not just as a conceptual tool, but as an operational reference for system implementation in complex care environments. The DHRM bridges the gap between high-level healthcare domain knowledge and low-level implementation details, supporting both conceptual clarity and operational application.

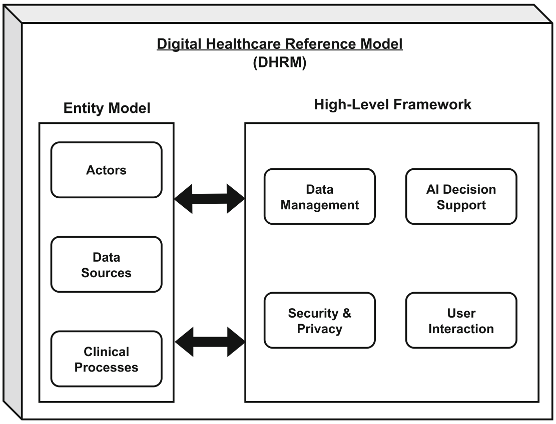

Fig. 3. Overall structure of the DHRM, showing the separation between the entity model and the high-level framework.

We defined the main actors, data objects and system elements in the entity model. We included patients, caregivers, healthcare professionals, study administrators, researchers and AI researchers as human actors. We also defined clinical studies, clinical data and digital health tools as operational entities. For each entity, we specified attributes and defined connections based on workflow and data dependencies. We extracted from use cases and refined them based on validation feedback. Figure 4 shows the entity relationship diagram that we constructed to formalise these definitions.

We organised the system responsibilities into five architectural layers: user interaction and service, AI-driven decision support, data harmonization and processing, data acquisition and interoperability and governance, security and compliance. We assigned each functional component to a layer based on its role in the digital healthcare workflow. For instance, patient and caregiver interactions were assigned to the user interaction layer, while AI models were placed within the

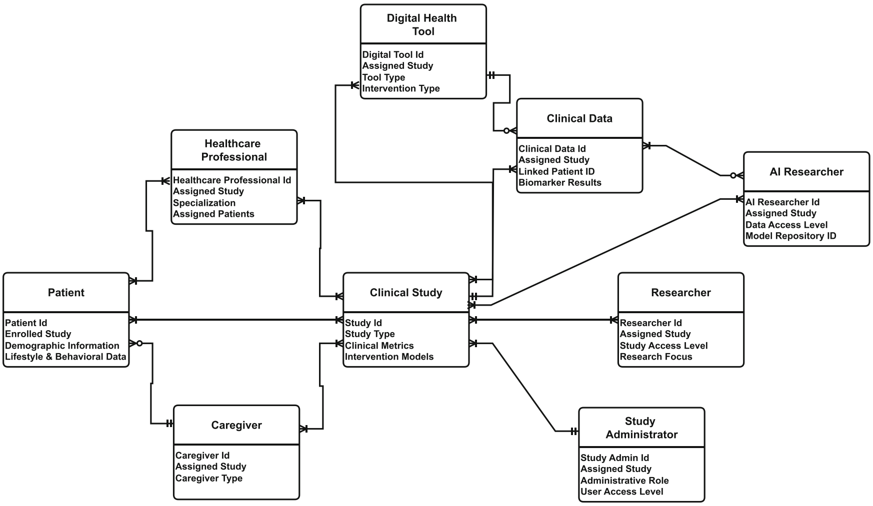

Fig. 4. Entity relationship model of the DHRM.

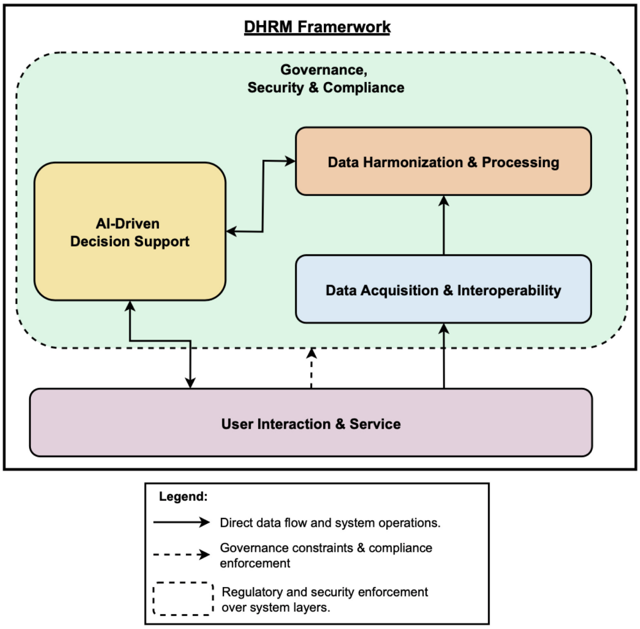

Fig. 5. High-level Architectural Framework of the DHRM, with layered responsibilities and operational flow.

decision support layer. Monitoring tools and data streams were mapped to the data acquisition layer, and governance mechanisms were aligned with the security and compliance layer. Figure 5 presents this layered segmentation showing how system components are organised within the DHRM framework. To maintain consistency between clinical roles and system responsibilities, we then mapped the entities from the domain model to their respective architectural layers. We placed patients, caregivers and professionals in the user interaction layer. We linked researchers and AI researchers to decision support and data processing. We distributed digital tools and administrators across interaction, compliance and logic layers. We placed clinical data and studies at the data acquisition and harmonization layers. This alignment ensures consistency between domain roles and system operations. Figure 6 shows the alignment between domain-specific concepts and system-level functionality.

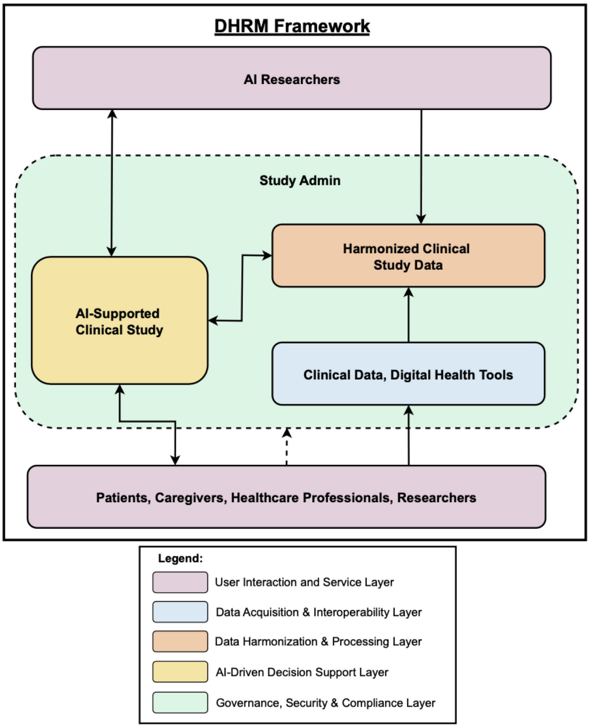

Fig. 6. Mapping of DHRM model entities across the Five Architectural Layers.

5 Conclusion and Future Work

This work advances a generalizable and operational reference architecture for digital healthcare systems, addressing critical gaps in methodological integration and providing a foundation for future research and deployment in age-related care. The model provides a replicable framework for deploying AI-enabled healthcare interventions, by formally structuring the interactions between patients, healthcare professionals, caregivers and digital systems. Future work will focus on expanding AI-based personalization, refining data harmonization strategies, and integrating advanced decision-support components. These developments aim to further support precision medicine strategies and enhance the scalability of digital platforms in age-related healthcare.

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Predicting Students' Critical Thinking Skills Using Machine Learning: A Comparative Study

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Abstract. This study investigates the feasibility of predicting students' critical thinking levels using machine learning techniques applied to academic and behavioral data. Recognizing critical thinking as a core competency in modern education is yet notoriously difficult to measure directly. This research aims to establish relationship between critical thinking proficiency and quantifiable variables such as an academic performance, extracurricular involvement, and course selection. A dataset comprising 500 anonymized student records was compiled and preprocessed to extract relevant features. Three predictive models—Linear Regression, Decision Tree, and Random Forest Regressor—were trained and evaluated using standard performance metrics. Among the three, the Random Forest model achieved the highest predictive accuracy with an R2 score of 0.84, substantially outperforming the Decision Tree (0.65) and Linear Regression (0.37) models. The results indicate that patterns in students' course preferences, levels of academic achievement, and engagement in non-academic activities collectively provide meaningful insights into their critical thinking capacity. These findings demonstrate that viability of data-driven frameworks for indirectly assessing cognitive skills and have potential applications in curriculum design, early intervention systems, and educational approach policy development. By leveraging accessible education data, the proposed approach contributes to more scalable, objective, and personalized evaluation strategies within broader domain of learning analytics.

Keywords: Machine learning · Linear Regression · Decision Tree · Random Forest · critical thinking · predicting students' critical thinking level

1 Introduction

Critical thinking has emerged as a vital competency in contemporary education systems, serving as a foundation for effective problem-solving, evidence-based reasoning, and adaptive decision-making. In academic and professional contexts alike, the ability to evaluate information critically, question assumptions, and formulate logical conclusions is increasingly valued. International educational frameworks, including the OECD Learning Compass and the Partnership for 21st Century Skills (P21), emphasize critical thinking as a core learning outcome necessary for global citizenship and lifelong learning.

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Despite its recognized importance, critical thinking remains a complex and abstract construct to define and assess. Traditional assessments methods such as written essays, standardized critical thinking tests, and subjective evaluations by instructors are limited by inherent biases, variability in scoring, and scalability issues. Theses challenges hinder the ability of educators and institutions to track and support student' development in this critical domain.

With the growing availability of educational data and advances in machine learning. There is an opportunity to approach the problem from a new angle. Academic records, course enrollment patterns, and involvement in extracurricular activities can serve as proxies for behavioral and cognitive traits. While such features may not measure critical thinking directly, they can potentially reflect tendencies associated with higher-order cognition, such as intellectual curiosity, self-regulation, and openness to diverse learning experiences.

This study investigates whether students' critical thinking level can be predicted using three observable dimensions such as academic performance (e.g., grades and GPA), extracurricular participation, and course selection behavior. A dataset of 500 students was collected and preprocessed to extract relevant features. Three predictive models such Linear Regression, Decision Tree, and Random Forest Regressor were implemented and compared to evaluate their effectiveness in estimating critical thinking scores.

The Random Forest model achieved the highest predictive performance, with an R2 score of 0.84, outperforming both Decision Tree (0.65) and Linear Regression (0.37). These results demonstrate that a nontrivial proportion of the variance in students' critical thinking levels can be explained through accessible educational data. The implications of this research are significant for the development of scalable, data-driven tools in education, enabling more personalized learning environments, targeted interventions, and deeper insights into cognitive development trends across diverse learner populations.

2 Related Work

Critical thinking plays a crucial role in higher education, influencing students' decision-making processes and their ability to navigate academic and professional pathways. The assessment of critical thinking has long been a subject of research in educational psychology and pedagogy. Classical approaches often rely on standardized tests such as the Watson-Glaser Critical Thinking Appraisal and California Critical Thinking Skills Test, which are designed to measure inference, analysis, evaluation, and deductive reasoning abilities. While these instruments provide structured frameworks, they are constrained by limited scalability, contextual rigidity, and the need for proctored environments, making them less feasible for continuous or large-scale application in modern learning ecosystems.

Recent studies have explored indirect assessment methods through behavioral and linguistic proxies. For example, Paul and Elder [1] advocate for evaluating students' reasoning within academic discourse and classroom engagement. Similarly, Liu et al. [2] proposed assessing critical thinking through written essays using natural language processing (NLP) techniques, identifying linguistic markers such as epistemic modality, counterarguments, and discourse coherence. These methods show promise in automating critical thinking evaluation but often require fine-grained textual data and complex feature engineering.

In parallel, the rise of educational data mining and learning analytics has prompted researchers to investigate the predictive potential of commonly available student data. Romero and Ventura [3] demonstrated how academic features such as attendance, GPA, and online interaction patterns could be used to forecast student outcomes and engagement. Studies such as that by Luo Z. et al. [4] incorporated features like students' basic information, performance at various stages of the semester, and educational indicators from their places of origin to predict and analyse of students' academic performance, a dimension closely aligned with critical thinking.

Machine learning techniques, especially ensemble models like Random Forest and gradient boosting, have gained traction in educational research due to their robustness in handling noisy, multidimensional data. For instance, Devi K. and Ratnoo S. [5] employed Random Forest classifiers to predict student dropout risks, showing haw behaviorally encoded patterns can reflect latent cognitive or motivational traits. However, the application of machine learning specifically to predict critical thinking using high-level academic and behavioral variables remains underexplored.

Numerous studies have explored the development of critical thinking skills and their impact on educational choices, with a particular focus on the integration of specialized curricula, interdisciplinary learning, and online education. For instance, Behar-Horenstein and Niu examined how critical thinking is fostered in higher education, concluding that programs designed to enhance analytical reasoning improve students' ability to assess their educational trajectories and make informed decisions [6]. Similarly, Evens, Verburgh, and Elen investigated the relationship between critical thinking levels and students' educational preferences, revealing that those with higher critical thinking skills are more likely to select interdisciplinary courses [7]. Gibson further supported this claim, emphasizing that students with well-developed analytical skills are better equipped to navigate educational opportunities and make deliberate course selections [8].

The impact of critical thinking on academic decision-making has also been explored in various cultural contexts. For instance, Yousef analyzed its influence in Arab countries, demonstrating that specialized critical thinking courses enhance students' confidence when selecting academic disciplines [9]. In the digital learning sphere, Condon and Valverde found that students who engage in critical analysis of information are more discerning in their online course selections [10]. Terenzini, Pascarella, and Springer expanded this perspective by assessing the role of academic environments in shaping critical thinking abilities, concluding that exposure to multiple courses emphasizing critical reasoning leads to more deliberate educational choices [11].

The effectiveness of instructional interventions designed to promote critical thinking has been widely debated. Ennis argued that structured programs significantly improve students' ability to align their course selections with future career aspirations [12]. This was reinforced by a meta-analysis conducted by Niu, Behar-Horenstein, and Garvan, who confirmed that educational programs explicitly targeting critical thinking skills contribute to more thoughtful academic decisions [13]. In addition, D'Alessio, Avolio, and Charles investigated the link between critical thinking and academic performance, concluding that students with strong analytical abilities make more informed choices regarding their coursework [14].

Research of Wolcott et al. has also explored the role of discussion-based learning and its effect on critical thinking [15]. Kalelioğlu and Gülbahar found that active participation in online discussions enhances students' awareness of their educational choices [16]. Similarly, Tang, Howard, and Austin examined how critical thinking training benefits managers, revealing that analytical skills are not only essential for career development but also for selecting appropriate educational programs [17].

A broader systematic review by Yuan et al. confirmed that the ability to make well-reasoned course selections is directly linked to students' level of critical thinking development [18]. In medical education, Pitt, Powis, Levett-Jones, and Hunter found that advanced analytical skills contribute to better academic progression and the selection of specialized medical courses [19]. Likewise, Chukwuyenum demonstrated that students with high levels of critical thinking perform better in mathematics due to their ability to develop strategic learning approaches [20].

The relationship between digital learning environments and critical thinking has also been explored. Temel found that distance education fosters critical thinking by encouraging students to analyze their academic pathways more thoroughly [21]. Additionally, Korkmaz and Karakus showed that students enrolled in critical thinking courses demonstrate a greater sense of responsibility when choosing educational disciplines [22]. Loes, Pascarella, and Umbach examined the impact of diverse educational programs, concluding that exposure to a variety of instructional methods leads to more informed course selections [23].

Furthermore, Ernst and Monroe analyzed the role of project-based learning in enhancing critical thinking skills, emphasizing that active engagement in educational projects results in more deliberate academic decision-making [24]. Lastly, Plummer, Kebritchi, and Leary explored the intersection of critical thinking, decision-making, and course selection, asserting that analytical reasoning plays a pivotal role in educational planning [25].

This study builds on and extends prior work by combining structured student data with predictive modeling techniques to estimate critical levels. Unlike NLP-driven approaches requiring extensive text data, our method leverages scalable, routinely collected educational records, making it more adaptable to institutional systems. The comparison of three models, Linear Regression, Decision Tree, and Random Forest Regressor, further contributes to the understanding of which algorithms best capture the non-linear and complex nature of cognitive traits within educational contexts.

3 Methodology

This section presents the empirical results obtained from the three predictive models, Linear Regression, Decision Tree, and Random Forest Regressor, and discusses their implications for educational assessment and cognitive modeling.

3.1 Dataset Description

The dataset used in this study comprises academic and behavioral data from 500 anonymized students across various undergraduate programs. Each student entry includes academic performance, course selection, extracurricular activities (see Table 1). Target variable is critical thinking score obtained from a standardized institutional assessment modeled after the Watson-Glaser framework.

Table 1. Dataset description

Feature Name	Type	Description
critical_thinking	Integer (1–100)	Target variable: measures students' critical thinking ability
gpa	Float (2.0–4.0)	Grade Point Average (GPA) on a 4.0 scale
extracurriculars	Integer	Quantity of hours of extracurricular activities a student participates in
course_selection	Categorical (Science, Arts, Business)	Encoded as 0 (Science), 1 (Arts), 2 (Business)

The dataset was preprocessed to handle missing values and normalize numerical features.

3.2 Model Selection

Three regression models were selected for comparison based on their interpretability, ability to capture non-linear patterns, and popularity in educational data mining. They are Linear Regression, Decision Tree Regressor (DT) and Random Forest Regressor (RF). Linear regression is known asa baseline model assuming linear relationship among features. Decision tree is a non-linear parametric model capable of capturing hierarchical, rule-based patterns. Random forest is an ensemble of decision trees that improves generalization by averaging outputs and redducing overfitting. Hyperparameters for DT and RF were turned using grid search and 5-fold cross validation.

3.3 Model Training and Evaluation

Models were trained on 80% training set and evaluated on the remaining 20% testing set. Performance was assessed using R^2 Score, MAE (Mean Absolute Error) and RMSE (Root Mean Squared Error).

This methodological pipeline demonstrates the viability of leveraging educational data and machine learning to estimate abstract cognitive constructs like critical thinking.

4 Results and Discussion

The performance of the models was evaluated using Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R2 score. Table 2 ssumarizes the results:

Table 2. Model Performance Comparison

Model	MAE	RMSE	R2 score
Linear Regression	3,76	5,73	0,37
Decision Tree	1,161	1,61	0,65
Random Forest	1,22	1,22	0,84

Random Forest achieved the best performance, with the lower error and highest R2 score (0.84). Decision Tree performed moderately well but was prone to overfitting. Linear Regression had the weakest performance, indicating that critical thinking skills do not follow a simple linear pattern (Fig. 1).

The Random Forest model demonstrated superior performance due to its ability to capture complex relationships between predictors and the target variable. Decision Trees performed reasonably well but were more prone to overfitting, while Logistic Regression was the least effective due to its assumption of linearity.

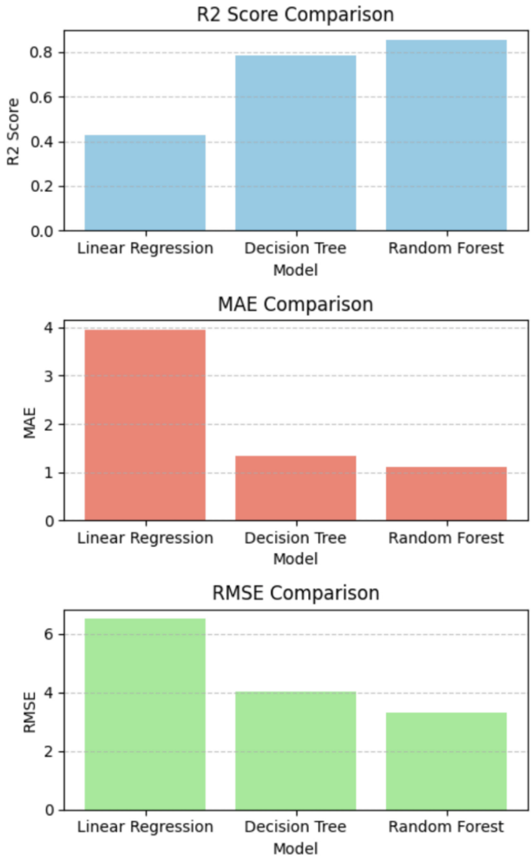

Fig. 1. Model Performance Comparison

Figure 2 illustrates the relationship between actual and predicted scores of critical thinking for three models.

Key observations include that Students with higher critical thinking scores were more likely to select Science courses, Extracurricular involvement had a weaker influence on course selection compared to academic metrics and GPA and critical thinking were moderately correlated, indicating a potential underlying factor influencing both.

Feature importance analysis revealed that GPA was the strongest predictor of critical thinking scores, followed by course selection. This aligns with previous findings that academic performance is closely linked to cognitive skill development [26].

Extracurricular involvement had the lowest importance score, suggesting that while participation in activities may foster social and leadership skills, it does not necessarily predict critical thinking abilities [27].

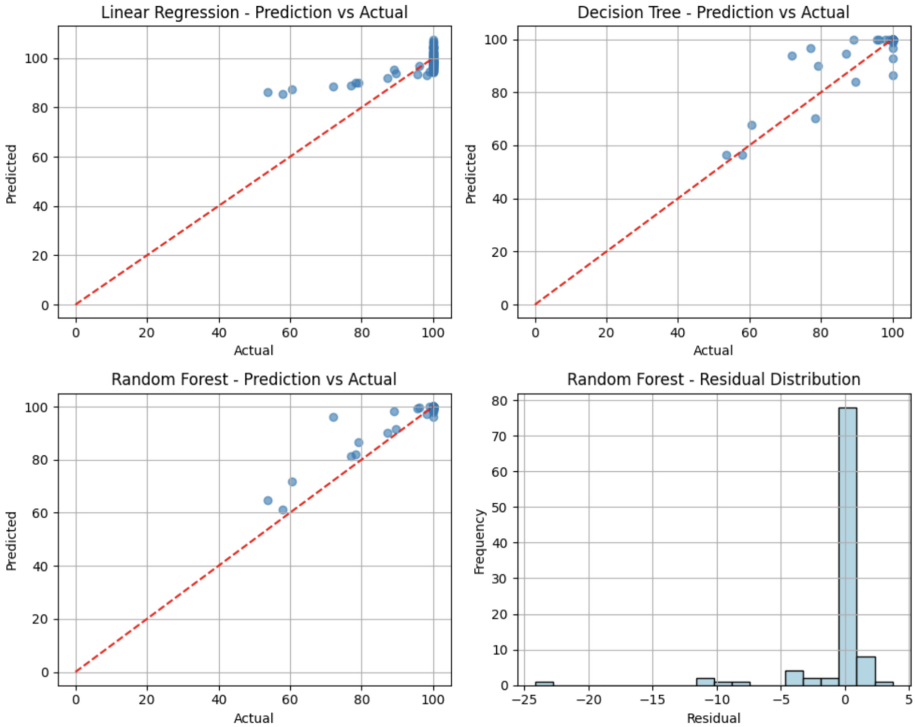

Fig. 2. Actual vs Predicted Critical Thinking Across three models

The results show that accessible student data can be leveraged to estimate critical thinking ability, supporting early intervention, curriculum design, and personalized learning. However, the dataset size and limited demographic diversity may restrict generalizability. The critical thinking metric, while standardized, may not fully capture multidimensional cognitive ability. The study did not consider psychological or socio-economic factors, which could improve prediction accuracy.

5 Conclusion and Future Work

This study highlights the predictive power of course selection, extracurricular involvement and academic performance in determining critical thinking skills. Random Forest emerged as the most reliable model due to its high accuracy and robustness.

Random Forest was the best predictor of critical thinking skills, demonstrating the advantage of non-linear models over traditional regression.

GPA was the most significant predictor, confirming that strong academic performance often correlates with higher critical thinking abilities.

Linear Regression performed poorly, reinforcing the complexity of cognitive skills development.

Future work relates to expansion the dataset introducing additional features, such as reading habits, debate participation, or problem-solving tests and comparison deep learning models, such as neural networks, to assess their effectiveness in predicting critical thinking skills. Future research could incorporate learning management system data, peer interaction networks, additional socio-economic and psychological factors to further refine the predictive model. Deep learning and explainable AI models could further enhance accuracy and interpretability.

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A.R.T.I.C.: A Conceptual Model for AR and UGC-Driven Social Media Marketing

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Abstract. This paper presents the development and demonstration of the A.R.T.I.C. model—a conceptual framework for integrating augmented reality (AR) and user-generated content (UGC) into social media marketing campaigns. The model is tailored to the dynamics of TikTok, where users act as both consumers and content creators. A critical review of existing marketing models (e.g., AIDA, Customer Journey, 5E Framework) reveals their limitations in addressing AR-specific interaction, co-creation, and platform-native behavior. In response, the A.R.T.I.C. model structures the engagement process into five phases: Attract, Relate, Trigger, Influence, and Convert. To illustrate the model, an AR lipstick filter was created using TikTok's Effect House platform. The prototype allowed users to visualize the product on their own faces and engage through recording and sharing, aligning with the model's stages. The paper compares A.R.T.I.C. to established frameworks and highlights its potential as a strategic planning tool for immersive marketing. The study is exploratory in nature and does not include quantitative metrics but sets the foundation for future empirical validation.

Keywords: Augmented Reality (AR) · TikTok Marketing · User-Generated Content (UGC) · Interactive Filters · A.R.T.I.C. Model

1 Introduction

In today's digital economy, social media marketing has become central to brand communication [1, 2]. Platforms such as TikTok provide highly visual and interactive environments that enhance user engagement through short-form videos and algorithmic personalization [3]. Augmented reality (AR), in particular, supports immersive product experiences that create emotional connection and influence purchase intent. Prior studies have shown that AR facilitates real-time interaction, strengthens customer-brand relationships [4, 5], and increases conversion likelihood by enabling users to visualize products on themselves [6–8].

This new marketing approach not only enhances user engagement but also helps build a deeper emotional connection with the brand [5, 9]. The application of such technologies is becoming a strategic tool for brand differentiation in highly competitive markets, especially in sectors like fashion and cosmetics, where personal experience strongly influences purchase decisions [10]. Brands that incorporate AR into their marketing

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strategies report increased consumer interest and engagement, which often correlates with higher purchase intent [8].

According to research, emerging technologies help customers make purchase decisions more easily while also emphasizing the importance of online influence and interactions [6, 11]. At the same time, digital activity traces are redefining sales and marketing strategies, prompting companies to continuously adapt and optimize their approaches to customer relationship management [12, 13]. Organizational success in the digital environment depends on the ability to respond to evolving conditions and to adopt innovations that offer value and unique user experiences [14, 15].

The rise of AR in social media marketing has enabled new forms of user engagement and personalized communication. In platforms like TikTok, users act not only as consumers but also as content co-creators, shifting the dynamics of traditional marketing.

Yet, existing models—developed before the emergence of AR and UGC—fail to reflect the visual, cyclical, and participatory nature of these interactions. Frameworks such as AIDA or the customer journey model often overlook the dual role of users as both audience and creators.

To address this, the present study introduces A.R.T.I.C.—a conceptual model designed to guide AR and UGC integration in platforms like TikTok. It reflects real-time, user-driven behaviour through five stages: Attract, Relate, Trigger, Influence, and Convert.

The model is demonstrated via a prototype AR lipstick filter created in TikTok's Effect House. This example explores how immersive experiences stimulate engagement, content creation, and potential conversion.

By framing interaction as a structured, repeatable process, A.R.T.I.C. contributes to business process modelling and digital marketing strategy. The paper proceeds with a review of marketing models (Sect. 2), prototype development (Sect. 3), model presentation (Sect. 4), and conclusions (Sect. 5).

2 Related Work and Theoretical Background

Various theoretical models have been developed to explain consumer decision-making and the stages of brand interaction. Among the most widely cited frameworks is the AIDA model (Attention – Interest – Desire – Action), which conceptualizes consumer response to advertising in a linear, sequential manner [16]. While historically influential, AIDA has limited applicability in contemporary digital contexts, particularly in social media platforms where behavior is non-linear and participatory.

Another influential approach is the Customer Journey Model, which considers the consumer's path from awareness to loyalty, incorporating all brand touchpoints throughout the interaction cycle. Unlike AIDA, this model allows for nonlinear behavior and offers greater flexibility. Experiential marketing plays a crucial role here by fostering emotional connections that encourage repeat purchases [17].

Models such as the 5E Framework (Entice, Enter, Engage, Exit, and Extend) emphasize the importance of emotional and interactive engagement. This framework aligns well with the core affordances of AR technologies, which offer immersive, emotionally resonant experiences. However, it lacks explicit focus on the purchase decision and measurable business outcomes [18].

The Hook Model, developed by Eyal [19], describes how habitual behavior is shaped by repeated triggers, actions, and rewards. It is useful for understanding behavioral engagement in digital platforms like TikTok, especially in UGC contexts. However, the Hook Model does not function as a strategic marketing model and lacks campaign-level planning utility.

The SOSTAC model (Situation, Objectives, Strategy, Tactics, Action, Control) offers a structured methodology for developing and managing marketing campaigns. While highly relevant in digital planning, SOSTAC does not address specific mechanisms related to AR engagement or user participation [20]. Lastly, the Technology Acceptance Model (TAM) explains how users adopt and engage with new technologies, focusing on perceived ease of use and usefulness. While applicable to AR environments in general, TAM does not capture emotional engagement, co-creation, or campaign dynamics essential to platforms such as TikTok [21].

These models, while valuable, do not fully reflect the visual intensity, personalization, and user activity that define modern AR-enhanced marketing environments. Their limitations are further analyzed in the next subsection.

AR has established itself as a key tool for creating personalized marketing experiences, offering interactivity that surpasses the capabilities of traditional advertising. The technology enables visual product testing in real-world settings, such as cosmetics or 3D models. Beyond visual impact, AR supports the development of emotional connections and long-term brand engagement [21].

In addition to AR, user-generated content (UGC) plays a key role in enhancing social media engagement. Unlike traditional media, platforms such as TikTok enable users to become co-creators of content, increasing authenticity, participation, and brand trust (Table 1).

Table 1. Effects of AR and UGC on User Engagement and Brand Communication

Effect	AR Description	UGC Description
Increased Engagement	AR captures user attention through interactivity [22, 23]	Personalization and co-creation encourage participation [29–31]
Emotional Brand Connection	Visualization on the user's face builds attachment [24, 25]	Users connect through shared experiences and values [31, 32]
Service Perception	AR creates innovative, personalized experience [26]	User-created content is perceived as more credible [33, 34]
Purchase Likelihood	AR positively influences purchase decision [27, 28]	UGC contributes to trust and influences decisions [32, 35]

Despite the significant potential of AR and UGC, existing strategic frameworks offer limited guidance for their implementation in immersive and co-created environments.

These limitations reveal the need for a new conceptual model that explicitly addresses AR-driven interaction and user participation—needs which the A.R.T.I.C. model aims to fulfill.

While the reviewed models have significantly shaped marketing theory, they exhibit notable limitations when applied to modern social media platforms such as TikTok, particularly in the context of AR and user-generated content (UGC). These limitations can be grouped into several categories:

- *Overly linear structure* – Models such as AIDA do not reflect the cyclical, viral nature of user interactions on platforms like TikTok. User engagement often happens in loops, fueled by trends and algorithmic rediscovery.
- *Lack of AR-specific mechanisms* – Frameworks like the Customer Journey Model and SOSTAC do not account for real-time visual simulations, face tracking, or personalization features enabled by AR filters.
- *Disconnection between experience and conversion* – Experiential models such as the 5E Framework focus on emotional engagement but lack clear mechanisms for driving users toward purchasing behavior.
- *Passive view of users* – Many traditional models treat users as recipients of brand messages, rather than as co-creators of content. UGC plays a critical role in engagement and reach on TikTok, yet remains outside the scope of most existing frameworks.
- *Platform-agnostic design* – The models generally ignore the affordances and constraints of specific platforms like TikTok, where short-form video, editing tools, and audio trends influence how users interact with brands (Table 2).

Table 2. Comparative Overview of Key Marketing Models in AR-UGC Context

Model	TikTok + AR Fit	Key Limitation
AIDA	Low	Linear; no UGC or interactivity
Customer Journey	Medium	Ignores AR features and co-creation
5E Framework	Medium	No purchase focus
Hook Model	High	Not a full strategy model
SOSTAC	Medium	Misses visual/user-driven engagement
TAM	High	No emotional or campaign-level elements

These gaps highlight the need for a new conceptual model that embraces co-creation, real-time visual personalization, and measurable progression from interaction to transaction. In this context, the A.R.T.I.C. model is proposed as a more suitable framework for structuring campaigns in AR-enhanced social media ecosystems.

The next section introduces a demonstrative prototype that applies these principles within a real TikTok campaign environment.

3 AR Effects on TikTok as a Tool for Driving Sales

In the context of digitalized consumer behavior and visually oriented social media platforms, AR offers new opportunities for driving sales by creating personalized and interactive experiences. Within the scope of this study, this potential was illustrated through the development of a demonstration AR lipstick effect, showcasing the capabilities of digital product "try-on" in the TikTok environment.

3.1 Creation of a Demonstrative AR Filter

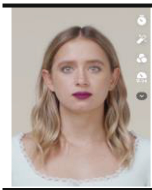
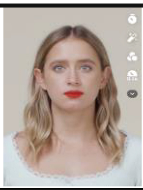
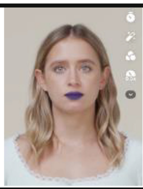
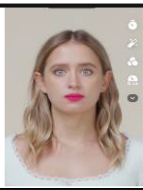
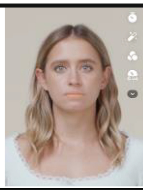
The AR filter was created using Effect House – TikTok's software platform for designing custom effects. No custom software was developed for this demonstration. Instead, the campaign prototype was implemented using Effect House, TikTok's proprietary AR filter creation tool:

- Selecting and configuring a lip tracker to enable color recognition and application
- Designing a custom lipstick mask using the shape editor and gradient layers
- Parameterizing the effect – intensity, matte/glossy finish, and transparency levels
- Exporting and publishing the filter on TikTok, with direct access via link and QR code

Five color variations were implemented: Plum Velvet, Red, Pink, Coral Peach, and Denim Dark Blue. Each filter was tested in a real TikTok environment to observe visualization, tracking, user interaction, response, and UGC engagement potential.

The prototype demonstrated how users can "try on" the product directly within the app—a process that combines visualization, personalization, and a gamified element, thereby shortening the path to purchase decision-making (Table 3).

Table 3. AR Filter Variants for TikTok with Direct Access Options

				
Plum Velvet #7D0552	Red #e50606	Denim #151B8D	Pink #ef9797	Coral Peach #FBD5AB

The observations made during the demonstrative campaign revealed several insights into user behavior that support the relevance of the proposed model:

- Users respond intuitively and positively when given the opportunity to visually simulate the product on their face
- The AR effect holds user attention for a longer period, especially when combined with the ability to record, share, and participate in a campaign

- Including a call-to-action (CTA) and a direct link to a product or store creates an immediate path to conversion
- Users are more likely to share content featuring the filter, particularly when it is visually appealing, novel, and includes a gamified element

These behavioral tendencies align closely with the stages of the A.R.T.I.C. model, particularly with the Relate, Influence, and Convert phases, validating the conceptual logic behind their inclusion.

These findings suggest that AR effects on TikTok simultaneously act as product demonstrations, emotional triggers, and UGC catalysts. This multifaceted role reveals a strategic potential not fully captured by traditional marketing models.

Traditional marketing models show specific limitations when examined through the lens of the demonstrated behaviour:

- Linear models such as AIDA do not account for the cyclical, interactive nature of user participation, nor the dual role of the consumer as both viewer and creator
- Passive communication models overlook the element of co-creation that defines TikTok content dynamics
- Models like TAM explain technology adoption but lack mechanisms to connect emotional interaction with transactional outcomes

These insights confirm the need for a new strategic framework that explicitly integrates (1) the user's active role in content creation, (2) the emotional and visual experience enabled by AR, (3) personalized interaction loops, and (4) the compressed path from engagement to purchase. These elements form the conceptual basis for the A.R.T.I.C. model, introduced in the next section.

4 The A.R.T.I.C. Model

To address the strategic limitations identified in existing marketing frameworks, this paper proposes the A.R.T.I.C. model—a conceptual structure tailored to the dynamics of AR-enhanced, co-created content in platforms like TikTok. The model organizes the user engagement process into five interlinked phases: Attract, Relate, Trigger, Influence, and Convert.

The A.R.T.I.C. model builds upon principles from behavioral marketing and consumer psychology, incorporating mechanisms of cognitive and emotional engagement, social proof, and viral content distribution. Unlike linear models such as AIDA:

- The user is not only a recipient but also a creator of content
- Each stage can serve as an entry point into the next (i.e., the model allows for non-linear dynamics)
- The experience occurs in real time and adapts to the user's behavior

The A.R.T.I.C. model is based on five interconnected phases (see Fig. 1):

While the model is demonstrated through TikTok-specific AR effects, its structure is adaptable to other AR-enabled platforms such as Instagram, Snapchat, or mobile apps that support user interaction and content co-creation. The model consists of five

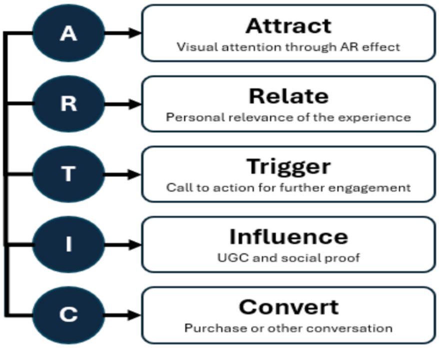


Fig. 1. Stages of User Engagement in AR-Based Campaigns

dynamic stages: **Attract** (visual impact through AR filters), **Relate** (personal identification via face visualization), **Trigger** (CTA activation), **Influence** (social sharing and trust-building), and **Convert** (purchase or redirection to transaction).

Particular emphasis is placed on the role of visual simulation (AR effect), which replaces traditional product demonstration and shortens the path to purchase. Combined with UGC, this approach expands marketing reach without requiring significant advertising budgets.

The demonstrative AR lipstick filter reflected each phase of the model: visual effects captured user attention (Attract), face visualization promoted identification (Relate), embedded CTAs guided action (Trigger), sharing options stimulated UGC (Influence), and clickable links facilitated conversion (Convert).

4.1 Comparison with Existing Models

Table 4. Comparative Mapping of A.R.T.I.C. and Established Marketing Models

A.R.T.I.C. Phase	AIDA Equivalent	Customer Journey	Unique Focus in A.R.T.I.C
Attract	Attention	Awareness	Visual immersion via AR and trends
Relate	–	Consideration	Personal simulation and identification
Trigger	Desire / Action	Intent	CTA embedded in AR interaction
Influence	–	Advocacy / Loyalty	Co-creation, peer-to-peer amplification
Convert	Action	Conversion	Direct hyperlink/conversion

The comparison highlights A.R.T.I.C.'s unique emphasis on co-creation, emotional engagement, and rapid conversion—features often missing in traditional frameworks such as AIDA (Table 4).

The A.R.T.I.C. model offers a balanced framework that combines theoretical foundations with actionable strategies, making it suitable for both academic analysis and real-world implementation. Its design reflects the specific dynamics of augmented reality and user-generated content in digital marketing environments.

By integrating behavioural, emotional, and technological dimensions into a cohesive structure, A.R.T.I.C. enables marketers to plan, execute, and assess immersive campaigns in a systematic way. The model's phased approach emphasizes interaction, measurability, and alignment with platform-native user behaviour.

5 Conclusion and Future Work

This study explored the strategic potential of augmented reality (AR) and user-generated content (UGC) in the context of TikTok marketing. A critical review of established marketing models revealed a conceptual gap in capturing the dynamics of interactive, visually immersive environments. To address this, we introduced the A.R.T.I.C. model—a five-phase framework (Attract, Relate, Trigger, Influence, Convert) that aligns behavioural, emotional, and technological dimensions into a structured approach to campaign design.

The model was demonstrated through a real TikTok AR filter, illustrating how each phase supports user engagement and contributes to measurable marketing outcomes. This confirms that AR, when combined with UGC, serves not only as a tool for attention capture but as a mechanism for personalization, co-creation, and conversion. This demonstration is exploratory in nature and does not include quantitative user analytics, which represents a limitation of the current study. Future work should include empirical testing with metrics such as engagement rates, click-through rates (CTR), and conversion data.

Future work may focus on validating the model across different product categories, consumer segments, and social media platforms. Longitudinal studies could further investigate the model's effectiveness in sustaining engagement over time or in triggering recurring user behaviour. In addition, integrating analytics and marketing automation systems may further enhance the applicability of the A.R.T.I.C. model in practice. The findings suggest that AR should be employed as an interactive engagement tool, not merely a visual enhancement. Branded effects require intuitive design and minimal entry barriers to facilitate participation. Effective campaigns should encourage UGC through mechanisms such as challenges and hashtags, supported by iterative testing and optimization. Finally, aligning AR initiatives with broader digital ecosystems ensures a coherent and seamless user journey across channels.

In conclusion, the A.R.T.I.C. model provides a theoretically grounded and practically applicable structure for immersive digital marketing. Its phased logic and adaptability make it suitable for designing campaigns that prioritize engagement, personalization, and measurable business impact. Furthermore, by aligning user behaviour with structured campaign stages, the model offers a valuable contribution to both marketing strategy and process-oriented digital innovation.

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Unmanned Aerial Vehicles: A Regulatory Compliance Perspective

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Abstract. The increasing number of unmanned aerial vehicles roaming in civil and other environments poses new challenges concerning both regulations (a legal framework that is insufficiently mature yet, air traffic management (for unmanned devices) that is insufficiently standardized yet, compatibility with manned aircraft, that is not always happening adequately, and so on) and public (safety, security, privacy, accountability, and so on). The lack of unified international standards, as well as differences in national legislation, make those challenges even more prominent. In tackling this problem, the current position paper delivers an analysis of the abovementioned challenges, taking into account the important goal of properly integrating unmanned aerial vehicles in civil airspace and also effectively managing them.

Keyword: Regulatory compliance · Public values · Civil traffic · Unmanned aerial vehicles

1 Introduction

International regulations and standards play a key role in the process of integrating UNMANNED AERIAL VEHICLES ("DRONES", for short) into civil airspace, as they provide a unified approach to safety, control and legal frameworks [1]. Different countries develop their own domestic regulations, but coordination at the international level is essential to ensure the effective and safe operation of unmanned aerial systems, especially in cross-border operations and international traffic.

One of the leading organizations responsible for global regulation is the International Civil Aviation Organization (ICAO). It has developed recommendations and guidelines for the integration of drones into existing airspace, focusing on issues such as identification, traffic management, and technical standards [2]. ICAO works closely with national aviation authorities to create an internationally recognized framework to ensure the safety of civil aviation and the effective management of air traffic.

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The European Union (EU), supported by the Aviation Safety Agency (EASA), has introduced a unified legislative framework that classifies drones according to the risk of operation and sets out different requirements for their registration, certification and operation [3], as follows: Drone operators must pass certain proficiency tests, comply with altitude and airspace restrictions and also with identification requirements; in addition, flight-restricted zones are considered, including airports, military sites, industrial areas and sensitive areas such as government buildings [4].

In the United States, the Federal Aviation Administration (FAA) is the primary regulatory body that oversees the use of drones [5]. The FAA has developed detailed regulations, including drone registration, operator licenses, safety requirements, and no-fly zones. Special emphasis is placed on the integration of drones into the air traffic control system and the development of unmanned air traffic management (UTM) technologies. In addition to domestic regulations, the FAA is actively involved in international standardization initiatives to facilitate global drone management.

Other countries are also developing their own national regulatory systems, which often follow the ICAO guidelines but may also include specific requirements. China and Japan have implemented strict regulations, especially regarding industrial and commercial drone applications. China, which is a leading drone manufacturer, has an extensive air traffic monitoring and control system, while Japan is mainly focusing on the development of autonomous drone systems for industrial purposes [6, 7,8].

In addition to national and international regulations, there are several standardization organizations such as ASTM International, RTCA, and EUROCAE that develop technical specifications for communication protocols, safety, and interoperability of drones. These standards help to unify technical requirements and facilitate the integration of unmanned systems into existing aviation infrastructure [9, 10]. The main challenge in international drone regulation remains balancing safety, security, and economic development of this sector. Different countries have their own specific approaches to regulation, which leads to inconsistencies on a global scale [11]. In the future, greater harmonization of rules is expected, facilitation of international drone operations, and the creation of advanced unmanned air traffic management systems that will ensure the safety and efficiency of airspace.

Hence, there are actual challenges concerning both regulations (a legal framework that is insufficiently mature yet, air traffic management (for unmanned devices) that is insufficiently standardized yet, compatibility with manned aircraft, that is not always happening adequately, and so on) and public (safety, security, privacy, accountability, and so on). The lack of unified international standards (except for the abovementioned ones that are nevertheless not equally applicable worldwide), as well as differences in national legislation, make those challenges even more prominent. In tackling this problem, the current position paper delivers an analysis of the abovementioned challenges, taking into account the important goal of properly integrating drones in civil airspace and also effectively managing them, for the sake of further stimulating the widespread integration of drones into civil airspace. The aspects examined highlight the need for a balanced approach in which technological progress is combined with clear regulations, high safety standards, the consideration of social and economic consequences, and so on. Such a balance could inspire possible solutions and strategies to overcome the abovementioned challenges.

The remainder of the current paper is organized as follows: Sect. 2 focuses on the regulatory integration of drones. Section 3 analyses potential solutions for a *safe* integration. Finally, we conclude our study in Sect. 4.

2 Regulatory Integration of Drones

The integration of drones into civil airspace is a complex and multifaceted process that requires synchronization between technological advances and regulatory frameworks [1, 4]. The main challenge lies in finding a balance between promoting innovation and ensuring safety, security and privacy. States and international organizations face a few difficulties related to the harmonization of legislation, the adaptation of existing aviation regulations and the creation of new control and surveillance mechanisms (Fig. 1).

Fig. 1. Challenges in regulatory integration of drones

One of the main challenges is the *lack of globally unified standards*. Although organizations such as the ICAO and the EASA are working to establish common principles, many countries apply different and often incompatible rules [2, 3]. This makes cross-border drone operations difficult and places constraints on the development of international services, such as drone deliveries or cross-border industrial inspections.

Other significant challenge is *air traffic safety*. Civil airspace is extremely busy, and the integration of drones requires the development of effective UTM [10]. Air traffic controllers must have reliable tools for monitoring and controlling drones, especially in areas with high flight intensity, such as large cities and the vicinity of airports. The introduction of automated drone control systems that can communicate in real time with civil aviation systems is a key aspect that is still being developed [12].

Security is other important aspect of regulatory integration. Drones can be used for illegal activities, such as smuggling, industrial espionage, or even terrorist attacks [13, 14]. This requires the introduction of strict identification and tracking mechanisms, such as remote identification (Remote ID) and geofencing, to prevent unauthorized flights into prohibited areas [15, 16]. In addition, governments and aviation regulators must develop effective methods to prevent unauthorized drone flights, such as systems to jam, intercept, or destroy hostile drones [17, 18].

Personal data protection and privacy are other serious regulatory issue. Drones with cameras and sensors can collect large amounts of information, including images of private property and individuals, without their explicit consent [19]. This creates legal and ethical dilemmas related to the right to privacy and data protection. In many countries, clear mechanisms for controlling the use of drones for surveillance are still lacking, which can lead to conflicts between drone operators and citizens.

Other challenge is the *lack of standardized technical requirements* for drones. Different manufacturers create devices with different characteristics, which makes it difficult to regulate minimum requirements for safety, reliability and interoperability [12]. The introduction of common industry standards for communication, navigation and collision avoidance systems is imperative to ensure the safe integration of drones into existing airspace.

Economic factors also play a role in regulatory integration. The development of new control and surveillance systems requires significant investment from both government institutions and the private sector [20]. Small companies that want to use drones for business purposes may face difficulties in covering the costs of compliance with new regulations, which may limit their access to the market.

Social perception of drones is also a factor influencing the regulatory process. Public concerns about safety, security, and privacy may lead to stricter restrictions and bureaucratic hurdles for drone operators [21]. Some countries are already witnessing public debates about the admissibility of drone deliveries, aerial surveillance, and autonomous unmanned aerial systems.

In the long term, successful regulatory integration of drones will require close collaboration between government institutions, aviation regulators, technology companies and society. Developing flexible and adaptable regulatory frameworks that can respond to rapidly evolving technologies and business models will be key to the effective integration of drones into civil airspace.

3 Towards Safety in the Airspace: Solution Directions

With the increasing use of drones in civil airspace, there is a need to create an effective air traffic management system that would ensure the safety, coordination and integration of drones with other participants in air traffic. The traditional air traffic management system (ATM) has proven to be unsuitable for handling a large number of autonomous aircraft with small dimensions, low flight altitude, autonomous control and a wide variety of their applications. A potential solution to this problem is the integration of the most effective technologies to ensure flight safety.

The development of the UTM system by NASA in collaboration with the US FAA improves the management and coordination of drone flights in low-altitude airspace. The conceptual model of this system proposed by NASA is based on decentralized coordination between drone operators, based on automated digital platforms for air traffic management. The rapid development of artificial intelligence and automation systems leads to a decrease in human intervention in these systems. Machine learning and neural networks are a means of optimizing drone routes and can predict and prevent possible potential conflicts. To achieve compatibility between different national UTM systems, the ICAO proposes to establish global standards and introduce a regulatory framework for the use of drones. The EU, through the EASA, has created a regulatory initiative called U-Space, which aims to define rules for managing drone traffic in Europe.

The key components required for integration into drone control systems are shown in Fig. 2:

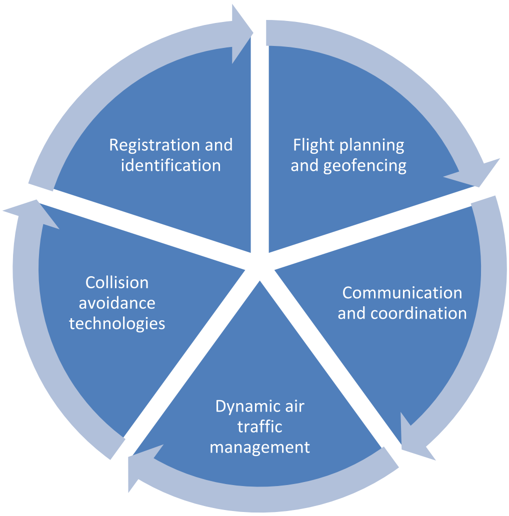

Fig. 2. Integration of drones in Civil Airspace

3.1 Registration and Identification of Drones

With the increase in the number of drones and their application in various fields, the need arises to implement effective mechanisms for control and regulation of their activities. The registration of drones and drone operators in a unified information system supports the safe operation and integration of drones in civil airspace by ensuring good control and accountability.

Drone identification is a technology that allows drones to be distinguished by their unique identification numbers. The main purpose of Remote ID is to provide traceability and control, thus facilitating law enforcement, aviation authorities and operators in managing drones. The identification number, location and flight status are broadcast by the drone in real time during the flight. With the introduction of more and more regulations, remote identification is becoming mandatory for many types of drones, especially those used for commercial and industrial purposes. This technology helps prevent unregulated flights, protect critical infrastructure and minimize the risk of air accidents.

3.2 Flight Planning and Geofencing

Drone operators should be required to submit a flight request in advance, describing the route (flight area) and the time interval of the flight. This would prevent conflicts with other airspace participants.

Geofencing is a technology that allows the creation of virtual boundaries in the airspace where drones can or cannot fly. It is used to limit access to certain areas and prevent unauthorized flights in sensitive areas, such as airports, military bases, government buildings and industrial sites. Geofencing works through built-in software algorithms in the drone's navigation systems. When the drone reaches the border of a prohibited area, it can automatically stop, change direction or return to its starting point. Flight planning combined with geofencing would provide increased safety and reduce the risk of incidents with manned aircraft.

3.3 Collision Avoidance Technologies

Automatic obstacle detection and collision avoidance technologies are crucial for airspace safety, especially with the increasing number of drones sharing the skies with manned aircraft, helicopters and other aircraft. Collision avoidance systems are based on a combination of sensors, artificial intelligence and autonomous decision-making algorithms that allow drones to detect and respond to potential obstacles in real time. This technology can be implemented with a variety of sensors using LIDAR, video surveillance, as well as various satellite navigation systems.

The use of LIDAR sensors allows the drone to scan its surroundings. These sensors provide precise information about the distance and shape of objects around the drone, creating a three-dimensional map of its surroundings. LIDAR is particularly effective when operating in complex environments, such as urban areas and indoor spaces, where navigation accuracy is critical.

Computer vision technology uses high-quality optical cameras and image processing algorithms. Through machine learning and neural networks, these systems can recognize various objects, determine their movement and predict potential collisions. Computer vision plays an important role in autonomous flight systems, improving the ability of drones to adapt to dynamic conditions and unexpected obstacles. In addition, ultrasonic sensors and infrared cameras complement lidar and vision systems, providing obstacle detection at close range and in adverse atmospheric conditions.

In addition to local sensor technologies, drones also rely on global navigation satellite systems (GNSS), such as GPS, Galileo, and GLONASS, which provide accurate information about the aircraft's location.

3.4 Communication and Coordination

The development of communication technologies also plays a significant role in preventing air accidents. Through Vehicle-to-Vehicle (V2V) communication systems, drones can exchange information with each other in real time, coordinating their movements and avoiding conflicts in busy airspace. In addition, Vehicle-to-Infrastructure (V2I) communication systems allow drones to receive data from control centers and ground stations that monitor air traffic and suggest optimal routes.

In summary, drones must maintain high-speed wireless communications with the operator, with drones in the airspace, with satellites and traffic control centers. These communications must be protected from cyberattacks and unauthorized access.

3.5 Dynamic Air Traffic Control

Air traffic control systems must monitor and manage changes in drone routes in real time. Achieving fully autonomous control is possible with the help of artificially intelligent algorithms that analyze data from all available sensors and make optimal decisions to avoid collisions and execute the desired trajectory. Through methods such as neural networks and machine learning, these algorithms can adapt to new scenarios and improve the ability of drones to respond quickly and effectively to emerging dangers.

Regulatory bodies, such as the ICAO and the EASA, are working to develop commonly accepted requirements to ensure that all drones, regardless of make and model, can interact with each other safely. With the advancement and integration of technologies discussed above, a higher level of autonomy and safety in unmanned aviation will be achieved, thus facilitating their integration into civil airspace.

4 Conclusions

Drones are playing a key role in various sectors. Their applications in logistics, healthcare, infrastructure monitoring and rescue operations demonstrate their high efficiency and potential to solve significant social and economic problems.

Air traffic management with drones requires the development of specialized systems such as UTM and U-space, which allow safe coordination between manned and unmanned aircraft.

Complex legislative and technical security measures are needed. Cases of unauthorized entry of drones into controlled airspace, collisions with manned aircraft and cyber threats highlight the need for stricter regulations, Remote ID and advanced technologies for incident control and prevention.

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