Model-based system engineering approach to design customized puzzle-based movable rack systems

Kasuni Vimasha Weerasinghe[1][0000-0002-9010-7017], Fabio Sgarbossa[1][0000-0002-9541-3515] and Andrei Lobov[1][0000-0003-2729-489X]

[1] Department of Mechanical & Industrial Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
kasuni.weerasinghe@ntnu.no

Abstract. The Puzzle-Based Movable Rack (PBMR) system is a new type of warehouse storage system that enhance the performance of Puzzle-based storage (PBS) systems with a new compact configuration where unit loads can be moved using racks on autonomous wheels in multi-directions. Various storage and movement policies are employed to optimize system performance, enhancing both density and throughput. To implement the proposed storage solution, we consider the PMBR system from an engineering-to-order (ETO) perspective. In this study, we investigate the design process of the PBMR system considering it as an ETO product with the support of a model-based system engineering approach. Utilizing methods and tools from the system engineering discipline facilitates defining warehouse functions, systems, and the necessary resources for system implementation. This enables comprehensive documentation of all stages of warehouse design. Furthermore, these warehouse models can seamlessly integrate with various analyses and existing domain knowledge, thereby bolstering warehouse design decisions. Further, There are the necessary technical and theoretical foundations in place for reliable PBMR design, which also offer insights into how the other ETO products and related system designs could be implemented.

Keywords: puzzle-based movable racks, warehouse design, engineering-to-order, model-based system engineering.

1 Introduction

Puzzle-based Movable Racks (PBMR) system can be introduced as an extended version of Puzzle-based Storage (PBS) system. The idea of PBS was initially developed as a result of studies on highly compacted storage systems that can maximize vertical storage space through compact configuration of stacking and arranging items. PBS systems are part-to-picker systems based on the well-known game 15-puzzle, in which the goal is to arrange 15 numbered tiles in a 4x4 grid in a sequential manner sliding the tiles into only one empty slot [1]. The tiles are similar to pallets, containers, totes, or other storage units in the PBS system. Puzzle-based systems allow unit loads to be shifted in four different directions by simply moving empty locations (escorts) where desired objects are easily accessible from an input/output point [2]. It is not practical to construct a warehouse using the space allotted for conventional aisles when there is a high demand for warehouse space. PBS systems offer a potential warehousing solution in these circumstances. These systems can achieve extremely high density compared to other storage systems. On the other hand, the throughput capacity of these systems is relatively low compared to other automatic solutions which use smart storage handling equipment.

There is a need for compact and responsive storage systems to deal with today's warehouse operations. Therefore, In recent years, the evolution of PBS which is known as PBMR was introduced and conceptualized through the collaboration between Logistics 4.0 lab and Norwegian company Wheel.me using the autonomous wheels developed by Wheel.me [3]. These autonomous wheels can be mounted on storage pallets, and it can be moved in any direction while resulting in high storage density and high throughput performance together. With its modular and reconfigurable design that maximizes spatial efficiency and adaptability, the puzzle-based movable storage systems represent a cutting-edge approach to logistics and storage management. Although the concept is still in its early stages and needs verification to show its viability and efficacy in practical applications and its capability to revolutionize storage solutions across a range of industries. PBMR system should be arranged to suit the required storage area size, shape, volume, and type of items that storage needs to be handled while maximizing storage capacity and improving accessibility. PBMR systems can be viewed as Engineer-To-Order (ETO) solutions since they may be tailored to meet specific customer needs. ETO techniques, in contrast to conventional off-the-shelf solutions, customize puzzle-based systems in terms of design, layout, and functionality to meet particular demands. To design the PBMR system, we investigate possible system engineering approaches. Model-Based Systems Engineering (MBSE) offers a systematic and all-inclusive framework that transforms the conventional approach to designing warehouse solutions. Engineers can produce intricate models that encompass the architecture, needs, procedures, and interconnections of the warehouse by utilizing MBSE methodologies.

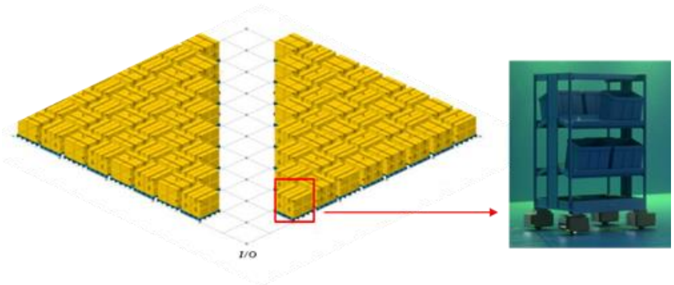

Figure 1: autonomous wheels robots mounted on storage racks (source: wheel.me)

The remainder of the paper is structured as follows. The second section will briefly discuss the concept of puzzle-based warehouse storage systems and puzzle-based movable rack systems. Also, it discusses the state of the warehouse designing process. At the end of the literature review research contribution will be explained. In Section 3, a specific warehouse design workflow will be suggested and the application of MBSE to warehouse design will be discussed. Using MBSE tools, the warehouse design workflow will be further refined in section 4. Section 5 concludes the warehouse design process using the MBSE tools and techniques and its role as a warehouse design decision support system. It will present a summary of the paper and conjecture on the future of these efforts.

2 Literature Review

This section discusses literature on different domains such as PBS, PBMR systems, and ETO operations in warehousing.

2.1 PBS and PBMR Systems

The concept of PBS was first introduced in 2007 [1]. In puzzle-based systems, loads can be moved in one of four directions by changing the escort places where desirable goods can be easily reached to an input/output location [4]. While striving to minimize the number of movements required to retrieve the items, the puzzle-based storage systems aim to achieve significant flexibility. The existing three main subcategories of PBS research are system analysis, design optimization, and operations planning and control [5]. The retrieval performance of the PBS system is the main focus of system analysis literature; this involves assessing expected retrieval times and contrasting them with those of conventional systems, as well as analyzing how the location of the escort affects retrieval time [1, 6]. Research on design optimization tends to concentrate on optimizing warehouse layouts under different storage policies and new technologies on sophisticated systems and more intelligent equipment [4]. An innovative PBS system that uses a small number of autonomous mobile robots (AMRs) was studied by [7]. The optimization of the retrieval path was mostly addressed through operations planning and control problems [2, 8]. According to recent studies on operational planning in PBS systems, retrieval times may be shortened by loosening the constraints set by the original setup. By adding more escorts, it is possible to create virtual aisles that permit specified loads to go continually. Previous research showed that employing a method that permitted escorts to be relocated simultaneously could reduce retrieval times [9].

Using the recent findings in PBS systems and unconventional aisle configurations as inspiration, Puzzle-based Movable Racks (PBMR) Systems were unveiled. The recent studies on PBMR attempted to develop a sophisticated robotic warehouse solution with the aid of autonomous wheels and investigate different movement policies and storage policies that might be required by the industries [10, 11]. Since the PBMR system is a completely new system that needs to be implemented, the aforementioned categories (system analysis, design optimization, and operations planning and control) should also be taken into consideration in practice as well as in theory. The initial studies of introducing the PBMR system with autonomous wheels and diagonal movements mainly address the system analysis [3, 10]. The application of a class-based storage policy with diagonal movement was studied by [11] to identify the ideal system dimensions to maximize the performance of the system. Therefore, that study mainly considers design optimization. The operation and control of the system is very crucial in both before and after the system implementation. In particular, complex systems require advanced control approaches. The study by [12] proposed to use a modular Petri Nets-based formalism for analysis of PBS setup for finding optimal control approaches. The study architect an adaptive PBS system that can dynamically adjust to changing configuration and/or control parameters.

2.2 Warehouse Design in ETO Perspective

We are approaching the design of Puzzle-Based Movable Rack (PBMR) systems from an Engineer-To-Order (ETO) perspective. Companies that develop and produce highly customized items employ the ETO manufacturing strategy. Certain standard business procedures like design, engineering, and manufacturing are quite complex due to the features of the ETO environment [13]. Designing a PBMR system also shares similar characteristics with ETO operations where the system should be configured and assembled understanding the customer requirements. With this customization, the system is guaranteed to properly match the client's inventory characteristics, space limits, and operational workflow. Furthermore, considering puzzle-based storage systems as ETO solutions promotes an in-depth understanding of the operational issues and goals of the client by enabling engineers and clients to collaborate iteratively. PBMR systems can become more than just storage solutions by adopting the ETO paradigm. Instead, they can develop into essential elements of streamlined warehouse operations that are customized to meet the demands of specific customers.

Since ETO products are often complex systems, optimization of them is more challenging. The optimization found in ETO solutions is often parameter-based, including normative and geometric parameters. To cut down on computation time and complexity, a modular approach can be expanded to a multistep optimization [14].

There is significant work has been done relevant to the warehouse solutions for ETO manufacturing customers. Also, different tools and methods have been employed to streamline the logistics and material handling of ETO operations [15]. We couldn't find significant work carried out considering warehousing as an ETO product even though it is customized based on the products and industry requirements. This study mainly focuses on developing customized storage solutions considering engineering and design aspects that fit with the different industry requirements.

This study makes significant contributions to the field of warehouse design, particularly concerning the integration of Puzzle-Based Movable Rack (PBMR) systems. This research provides important insights into optimizing warehouse operations by addressing the research questions of comprehending the various requirements involved in designing a warehouse solution with PBMR systems and using a system engineering approach to analyze the diverse needs of different industries for customized warehouse solutions. First, this study provides a thorough understanding of the many requirements of PBMR systems, such as material handling procedures, operational workflows, and geographical restrictions. This understanding paves the way for the development of effective and flexible warehouse solutions. Second, by employing a system engineering methodology, this study makes it possible to analyze the many needs found in various industries systematically and to pinpoint similarities, differences, and particular challenges. This study offers a comprehensive framework for creating customized warehouse solutions that satisfy the unique requirements of many sectors while optimizing efficiency, productivity, and adaptability by bridging the gap between theoretical knowledge and practical application.

3 Methodology

3.1 Requirements for designing the PBMR system

A comprehensive review of existing research, case studies, and industry best practices on both warehouse storage systems and PBS systems will help to identify the parameters for designing a PBMR system. Through the review of literature pertaining to warehouse architecture, material handling systems, and storage optimization approaches, engineers can get significant knowledge regarding the particular requirements and obstacles linked to the execution of puzzle-based solutions. This procedure entails determining important performance metrics including labor productivity, inventory control, throughput, and space usage in addition to comprehending the limitations and restrictions of the current storage systems. Engineers can recognize new directions, creative solutions, and effective applications of puzzle-based moveable rack systems across a range of sectors by conducting a methodical literature review. By making use of this information, they can precisely specify the specifications and design characteristics required to create a tailored solution that satisfies the particular requirements and goals of the warehouse environment. The following diagram was created considering past research and industry practices.

The previous studies [16] stated that there is no standard protocol or workflow for warehouse design. Their research provided the following common, necessary steps: (1) identifying the data that is required and creating the instance data to ascertain the needs; (2) analyzing the data to ascertain the warehouse requirements; and (3) designing the handling units and the fundamental flow plan through the warehouse;(4) choosing, sizing, and setting up technologies to support the flow pattern;(5) arranging warehouse systems physically; and(6) conducting a thorough performance review of the warehouse. Apart from the study by [16], we got insights from the domain of warehouse and order-picking system designs [17] and compared those conventional system design types with the PBMR system in order to identify the amendments required for the design workflow of the PBMR system.

The design process for puzzle-based movable racks is a methodical procedure that aims to produce effective and versatile storage solutions that are customized to meet the unique requirements of warehouse environments. To determine important design factors, it usually starts with a careful examination of the warehouse space, inventory properties, and operating requirements.

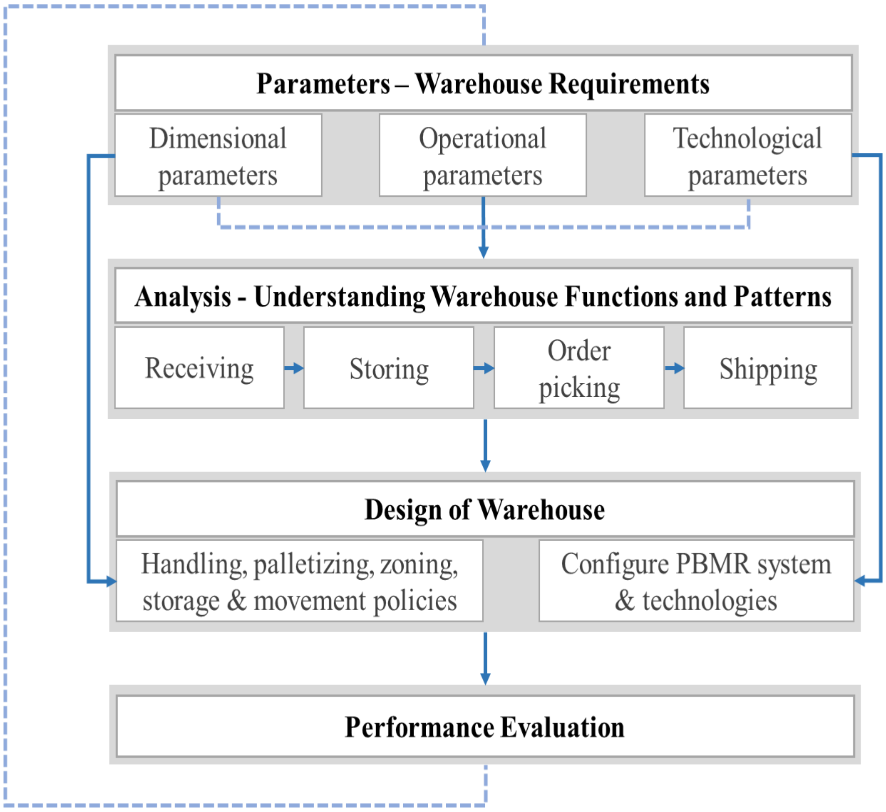

Figure 2: PBMR Design Workflow

After the requirements are determined, engineers construct conceptual designs and test various configurations using modeling and simulation tools like SysML or UML. In order to visualize the suggested rack configurations and evaluate their viability in terms of space utilization, accessibility, and material handling efficiency, this phase may entail the creation of 3D models and simulations. Refinement of the designs is ensured through collaborative conversations and feedback loops with stakeholders, guaranteeing alignment with operational objectives and constraints. Once the design is complete, engineers move on to the prototyping and testing phases, building and testing virtual or physical prototypes and putting them through rigorous testing to ensure functionality and performance. Iteration and refinement are essential elements of the workflow, enabling ongoing enhancement and optimization of the puzzle-based moveable rack design to satisfy the changing needs of warehouse operations. The parametric diagram depicted in Figure 2 provides an overall interface to modeling the design process of the warehouse with the PBMR system. Each subsection of the diagram can be further modeled and evaluated. Through the consideration of these parameters during the warehouse design process, businesses can guarantee that the ultimate solution is in line with customer demands and operational requirements, culminating in a customer-centric, efficient, and economical warehouse design.

3.2 Modeling tools and techniques

The tools provided by Model-Based Systems Engineering (MBSE) are extremely helpful when creating PBMR systems that are suited for warehouse settings. The complex parts and interactions inside these systems can be captured and represented in an organized manner thanks to these tools. Engineers can build detailed models of the architecture, behavior, and specifications of puzzle-based storage solutions by applying MBSE. Prominent MBSE tools for modeling, simulation, and analysis, such as SysML (Systems Modeling Language), Simulink, and Enterprise Architect, have strong capabilities that let engineers envision and validate system designs before putting them into practice. With the aid of these tools, collaborative design efforts may be facilitated, and diverse teams can easily discuss and refine their designs, resulting in storage systems that are optimized for effectiveness, warehouse space usage, and operational performance. Engineers may tackle the intricate problems that arise when creating PBMR systems by using MBSE tools. This allows them to provide precise and efficient solutions that satisfy the various requirements of warehouse operations.

These models, which offer thorough research, simulation, and validation of design choices before implementation, dynamically reflect the warehouse system. Using graphical representations to aid stakeholders in understanding complex system behavior, MBSE fosters cooperation across multidisciplinary teams. Moreover, MBSE promotes traceability by guaranteeing that every design element is linked to the corresponding constraint or requirement. By the design process, this enhances transparency and accountability. Generally speaking, MBSE provides engineers with the resources they need to create ideal warehouse systems that more successfully, reliably, and economically meet client needs.

Systems engineers may capture, analyze, and communicate system requirements and designs with the use of a comprehensive set of modeling tools provided by SysML, or the Systems Modeling Language. Block Definition Diagrams (BDD), Internal Block Diagrams (IBD), Activity Diagrams, Sequence Diagrams, State Machine Diagrams, Parametric Diagrams, and Use Case Diagrams are a few examples of these modeling methods. [16] used these tools to illustrate to design of the traditional warehouse. In the next section, we explain how we used these tools to design the PBMR system.

4 Models and Frameworks Development

As mentioned earlier PBMR design workflow can be further refined using MBSE tools. In MBSE, creating diagrams to identify dimensional parameters is essential for understanding the requirements and constraints of a system. SysML uses different diagrams with simple block constructs that can be used in several ways to define the warehouse domain semantics. We used types of several diagrams to refine the warehouse design process and generated these diagrams using Visual Paradigm software.

4.1 Internal block diagrams (IBD)

An intricate picture of a system's internal architecture can be obtained via IBDs, which illustrate how blocks are connected by ports and connections. The flow of data, energy, or other resources between the blocks in the diagram can be specified by engineers. Three IBDs were created for dimensional, operational, and technological requirements under this study. Through the diagram of Figure 3, engineers can systematically identify and prioritize dimensional requirements, ensuring that the design of the puzzle-based movable rack system aligns with user needs and operational goals.

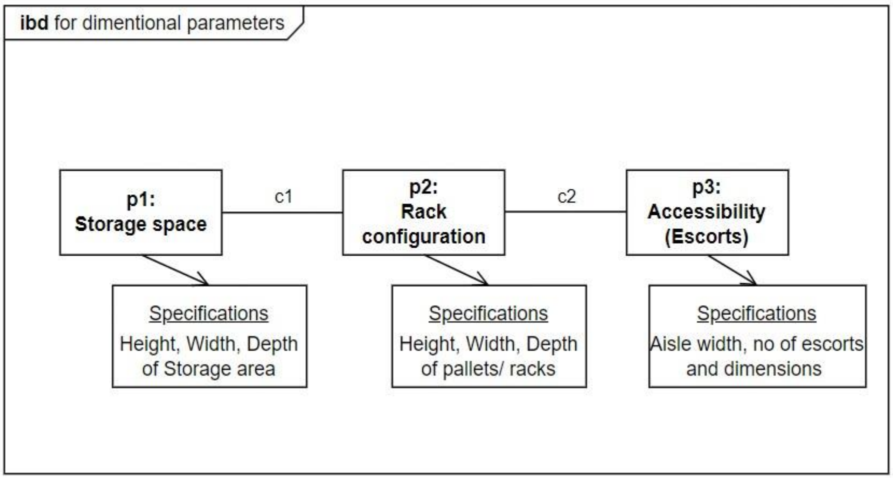

Figure 3: Internal block diagram for dimensional parameters

The next IBD on operational requirements is illustrated in Figure 4. The operational characteristics of warehouse design cover a broad spectrum of elements essential to a warehouse facility's smooth operation. These factors cover things like labor efficiency, material handling equipment accessibility, throughput, inventory turnover rate, order fulfillment speed, and storage capacity. A warehouse's maximum amount of inventory is referred to as its storage capacity, while the pace at which items move through the facility is measured as its throughput. The efficiency of inventory management techniques is reflected in the inventory turnover rate, which measures the speed at which inventory is sold and replenished. Meeting client demand and guaranteeing on-time delivery depend heavily on order fulfillment speed. The productivity and task performance of warehouse employees are evaluated by labor efficiency. Safety precautions are necessary to safeguard employees, avert mishaps, and guarantee adherence to legal requirements. The ease of mobility and agility within the warehouse is determined by the accessibility of material handling equipment, which has an impact on overall operational efficiency. Warehouse designers may build facilities that are safe, sustainable, and productive in addition to being efficient and productive by taking these operational aspects into account and optimizing them.

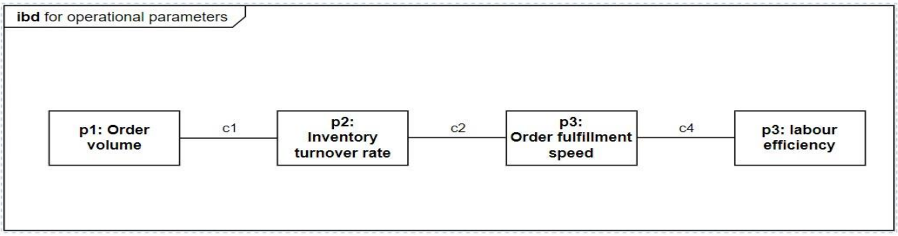

Figure 4: Internal block diagram for operational parameters

Puzzle-based movable rack systems' productivity, dependability, and adaptability in warehouse settings are greatly influenced by technological factors that are integral to their design and operation. The internal block diagram in Figure 5 illustrated help to refine the system's mechanical architecture, automation capacities, interface with warehouse management systems (WMS), safety features, energy efficiency, scalability, maintenance needs, and data analytics capabilities which are covered by the technological characteristics.

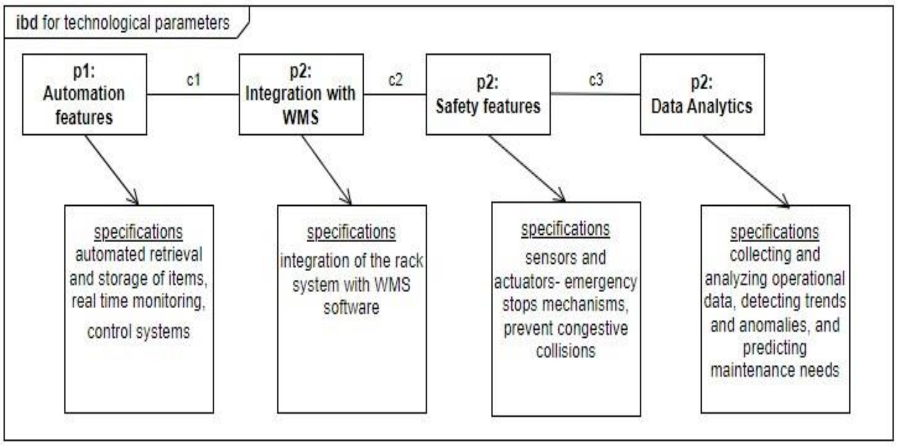

Figure 5: Internal block diagram for technological parameters

Automation features and control systems are the core behind the overall performance and functionality of the system. While safety elements like sensors and actuators prioritize system safety, integration with WMS allows smooth communication and data exchange. Furthermore, system performance improvement and predictive maintenance are made possible by data analytics capabilities. Designers can create novel and efficient puzzle-based movable rack systems that meet the changing needs of contemporary warehouse operations by taking these technological characteristics into account and optimizing them. These comprehensive details of the PBMR warehouse design are made possible with the use of MBSE.

4.2 Block definition diagrams (BDD)

By utilizing blocks to represent components, subsystems, or other entities, BDDs enable engineers to specify the structural parts of a system. The qualities, characteristics, and connections between the blocks in the diagram can be specified by engineers.

The warehouse functions are illustrated using BDD as depicted in Figure 6. The primitive functions necessary to consume the InFlow and generate the OutFlow are specified for each warehouse in MBSE in Warehouse Design.

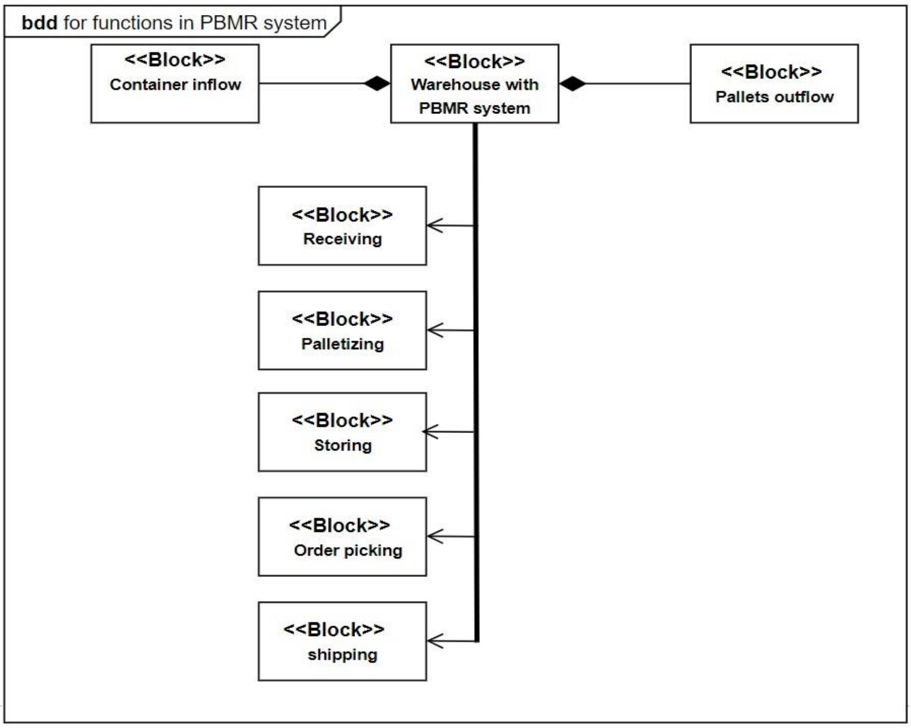

Figure 6: Block definition diagram for main functions

4.3 Use case diagrams

Use case diagrams illustrate the interactions between actors (users) and the system's use cases (functional requirements), giving a high-level picture of the functional requirements of a system. Use case diagrams can be used by engineers to specify the needs and scope of the system. Additionally, this facilitates communication and collaboration among stakeholders, fostering a shared understanding of dimensional parameters, storage policies, function, performance, and system integrations and their impact on system design.

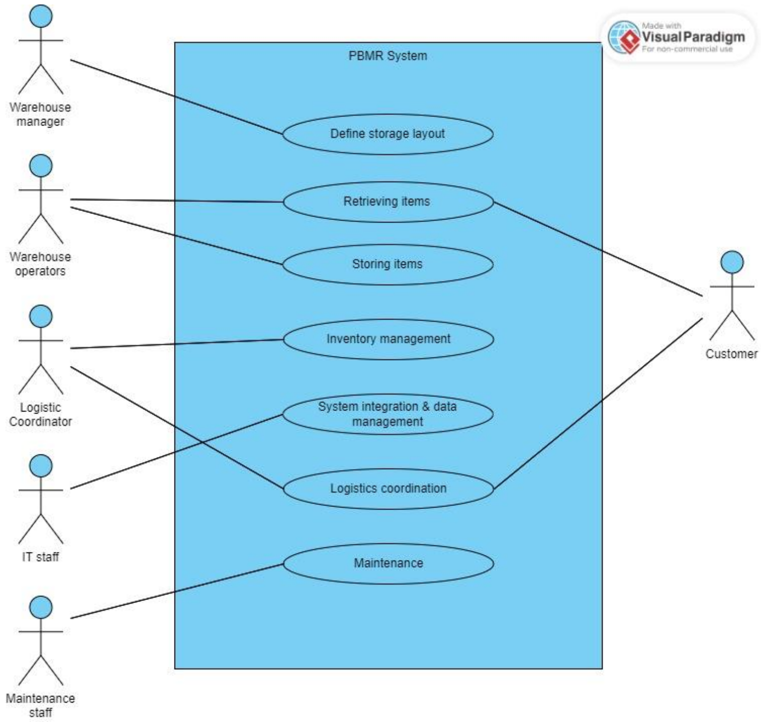

Figure 7: User case diagram for puzzle-based movable racks system

Using SysML modeling tools, engineers may generate full models of intricate systems, facilitating efficient communication, analysis, and design across the entire system development lifecycle.

Then, we collide user cases with CRUD (create, read, update, delete) operations to discover and implement necessary functions in a structured and comprehensive manner. It is imperative that CRUD processes be integrated with use cases while designing the PBMR system. Use cases ensure that all user requirements are considered by outlining the precise tasks and interactions users will have with the system. The fundamental acts of create, read, update, and delete on data entities such as items, storage locations, and inventory records are grouped together called CRUD. This combination guarantees that the right data operations are in place to serve each use case, resulting in a functioning and well-organized design. This methodology also helps to establish explicit testing processes to confirm that the system supports scalability, satisfies user needs, and makes maintenance easier. Overall, CRUD's integration with use cases guarantees a solid, user-centered design that can effectively manage and enhance the functionality of the storage system.

Table 1: CRUD matrix of the use cases designing the PBMR system

	Entity								
User case	**Item**	**Storage location**	**Storage layout**	**Inventory record**	**Maintenance record**	**System configuration**	**Data record**	**Shipment record**	**Schedule**
Define storage layout		RUD	CRUD						
Retrieving items	R	RUD							
Storing items	CUD	RUD							
Inventory management	RUD			RUD					
System integration & data management						CRUD	CRUD		
Logistic coordination								CRUD	CRUD
Maintenance					CRUD				

5 Conclusion

As a newly introduced sophisticated storage solution, puzzle-based movable rack systems require a structured design process. Since PBMR is still a concept it should be feasible to implement considering the industry requirements. Therefore, we consider the PBMR system as a large-size ETO product because it shares similar characteristics as the other ETO products. Designing such a system needs different factors to be considered to gain a sophisticated reliable outcome. When building a puzzle-based movable rack system, using model-based Systems Engineering (MBSE) tools provides an organized and methodical approach that has many advantages. Important design characteristics can be identified and prioritized thanks to MBSE and SysML which complete requirements analysis facilitation throughout the design process. Engineers are better able to visualize, simulate, and assess various design choices because they have a deeper understanding of the complexities of the puzzle-based movable rack system through the creation of accurate models of the system architecture, behavior, and requirements. Moreover, MBSE encourages multidisciplinary teamwork among members with different areas of expertise, which fosters cooperation, communication, and synergy throughout the design process. MBSE enables engineers to design unique, effective solutions that satisfy the unique requirements and goals of warehouse operations through iterative refinement and optimization. In the end, designers can create puzzle-based movable rack systems that are not only creative and dependable but also in line with the changing needs of contemporary supply chains by utilizing the concepts and techniques of MBSE.

As an object-oriented programming language, SysML is essential in the context of determining design artifacts considering the physical and logical model of the actual warehouse with PBMR system. It offers an appropriate platform for defining the common semantics in a way that is understandable by various stakeholders or decision-makers.

Future research can advance the state-of-the-art in the design and development of customized puzzle-based movable rack systems by exploring the validation and verification of MBSE tools. These initiatives can ensure accuracy, reliability, and compliance with industry/customer requirements. This might involve developing formal verification methods, simulation-based validation procedures, and empirical validation studies carried out in real-world warehouse environments.

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