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An Exploratory Study on Material Handling Systems Design and Analysis

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Abstract

The material handling system is considered as an important part in facilities design as it is the step following the design of processes and workstations inside the layout, plays a role in optimizing operational efficiency, reduces costs, facilitates and collaborates and connects between supply chain different elements. This study aims to provide a complete understanding of material handling systems. The primary objective of this exploratory research is to classify and characterize the material handling equipment and understand the difference between the equipment and their effect on system design and analysis. The study focuses on the methodologies and techniques of selecting material handling equipment. Through identification, categorization, and comparison, the aim is to highlight the potentials of different approaches. Identifying the modeling techniques is a crucial part for developing accurate representation of the systems supporting the design and analysis. Some findings from the literature review were gathered and a framework for material handling system is initialized.

Keywords
Material Handling, Material Handling Equipment, Material Handling systems, Design and Analysis, Optimization.

1. Introduction

Material handling is an important part of the facility, as the material handling process selection follows the selection of manufacturing processes and selecting the workstations. Material handling is the process of moving material to the right place, at the right time, in the right amount, in the right sequence, and in the right position and conditions (Stephens & Meyers, 2013). The process of material handling includes movement, storage, control, protection of materials and the products through manufacturing, distribution, consumption, and disposal processes. Material handling plays a vital role in enhancing the efficiency, reducing costs, optimizing operations within the facility. According to The American Society of Mechanical Engineers (ASME), material handling equipment is defined as the art and science including the packaging, movement, and storage (Tompkins et al. 2010).

1.1 Principles of Material handling equipment

Practical applications of material handling equipment are important, as some of the mathematical models fail to offer comprehensive solutions. These principles summarize the fundamentals of material handling practices, providing guidance and perspective to material handling systems design. The principles are: planning principle, standardization principle, work principle, ergonomic principle, unit load principles, space utilization, system principle, automation principle, environmental principle, and life-cost principle (Tompkins et al. 2010).

The planning principle is considered as a plan and group of actions before the implementation; basically, a material handling plan defines the material using (What) and the moving action (Where and when) is defined by the method (How and who). Standardization principle includes minimizing diversity and customization in the utilized methods and equipment. Work principle is quantification of work involving material flow (Volume, Weight, and count per unit of time) times the distance moved. The ergonomics principle aims to design the work or work conditions to align with the worker's capability and make the workstation, material handling equipment more user-friendly. The unit load principle refers to a single object such as a pallet, container, or tote that can be stored or handled in one time, ignoring the number of items representing the load itself. Space utilization principle counts the material handling system as three dimensions, and therefore, it is counted in cubic feet. According to the system principle, the material handling system is defined as a collection of units that can interact, dependent on each other. In automation principle, automation involves using electronics, electromechanical devices, and computer-based systems to control production and services by linking mechanical operations through programmed instructions. The environmental principle aims to eliminate the wastes negatively affecting the system and to avoid wasting natural resources. The life-cycle cost principle includes the financial transactions from the initial plan cost until completing, or replacing, the existing method. Logically, all principles do not fit all material handling systems projects. They can be used as a checklist for material handling systems designers, so the application of the principles to day-to-day activities can improve material handling solutions (Tompkins et al. 2010).

1.2. Design of material handling systems

The process of designing material handling systems has different considerations such as the handled material, requirements for production department, warehousing, and distribution, existing technology, facility layouts, and labor. The primary goal of designing material handling systems is minimizing handling cost, maximizing the efficiency and productivity.

The design of material handling systems does not depend on the mathematical models, as mathematical models usually do not reach the qualitative approach of the material handling systems. Therefore, the material handling systems designers depend on the principles mentioned in section 1.1. Successful design for material handling systems should involve some considerations such as defining the complexities of material handling systems (MHS), purpose, and functions, life cycle environment, transaction, and attributes of equipment (Mohsen & Hassan, 2010).

To summarize, the main objectives of designing material handling systems are improving efficiency, minimizing errors, and providing good work conditions aligning workers' capabilities.

The intended benefit of this research is to explore and consolidate knowledge of the material handling various aspects to help in the processes of design and analysis of MHS. By summarizing and organizing the key principles, methodologies, and design practices, the paper can serve as a valuable reference for researches, engineers, and practitioners to clarify how the material handling decisions, affect efficiency, cost, ergonomics in the facility, and providing a comprehensive guide that highlights the limitations in current facilities.

The review aims to identify the gaps and recommend the areas for future research that could enhance the efficiency and effectiveness of the material handling systems.

2. Methodology

2.1. Initial plan

The goals of the study should be the following:

1. Classification and characterization of material handling equipment.
2. Identification, categorization, and comparison of material handling selection methodologies and techniques.
3. Identification of available material handling modeling techniques.

The mentioned primary goals of the research help to open the path for modeling and development represented in the following:

1. Modeling of material handling equipment and systems.
2. Analysis and design of material handling systems.
3. Address industrial setups such as Lean and Industry 4.0.

Application and improvement can be represented in:

1. Field case study
2. Simulation
3. Review and refinement

The remainder of this study is organized as follows: a literature review on classification and characterization of material handling equipment, identification, categorization, and comparison of material handling selection methodologies, and identification of available material handling models' techniques. Afterwards, the methodology is proposed after gathering the findings through the various articles. In the last section, conclusions are drawn and summarized.

2.2. Literature review and selection criteria

The studies are chosen based on the key words and the primary objectives of this study, which involve the following:

1. Classification and characterization of MH equipment.
2. Identification and categorization, and comparison of MH selection methodologies and techniques.
3. Identification of available MH modeling techniques. The keywords used were: material handling equipment, material handling systems, material handling selection, modeling techniques, categorization of MH equipment. The keywords used were: material handling equipment, material handling systems, material handling selection, modeling techniques, categorization of MH equipment.

The keywords used were: material handling equipment, material handling systems, material handling selection, modeling techniques, categorization of MH equipment (Figure 1).

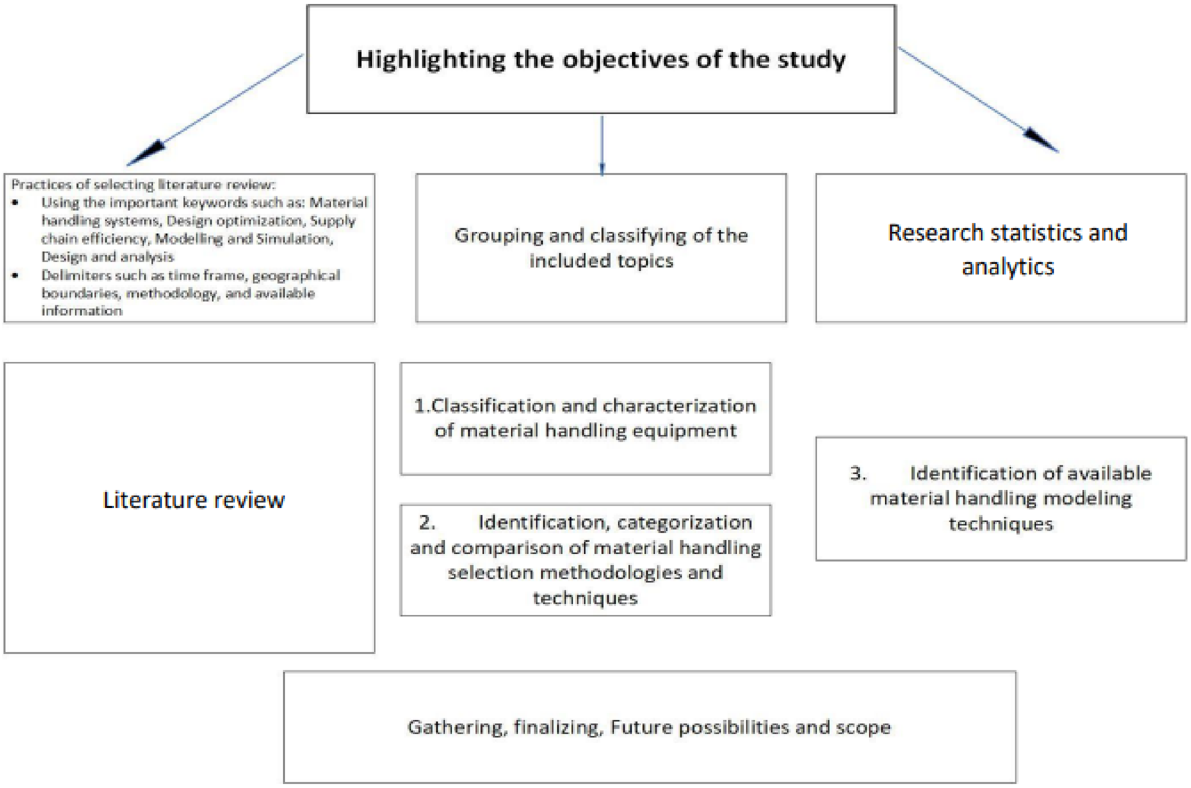

Figure 1. Initial plan for the exploratory study of material handling systems design

3. Literature review

The study by Asef-Vaziri and Laporte (2005) provides and highlights an overview of facility layout problems and discusses various aspects, such as different types of layout problems, methodologies used for solving them, and applications in different industries. Regarding the material handling part, it emphasizes that MH costs can significantly affect manufacturing costs. According to estimates, 20-50% of manufacturing expenses are associated with material handling. The challenges of material handling involve arranging facilities along handling paths and selecting suitable equipment. The literature review discusses different types of patterns for MHE, including single row, loop, multi-row, and open field layouts. In urban areas, where horizontal space is limited, multi-floor layouts are considered. The study reviews some challenges such as backtracking and bypassing in flow-line layouts, which impact product flow efficiency. Backtracking is the movement of the part to previous workstations or different facilities, while bypassing occurs when parts skip certain facilities or workstations. The paper discusses and suggests various strategies to minimize or even avoid backtracking and bypassing. Pick-up and drop-off parts determination for the parts adds another stage of complexity, and by simplifying the placement, the complexity can be reduced. The review provides insight into the complexities of MHS and the different design considerations involved in optimizing facility layout for smooth material flow.

The study by Pérez-Gosende, Mula, and Díaz-Madron˜ero (2021) previews the approach and planning stage and characteristics of production facilities by configuring the material handling system (MHS). The review configured MHS as a single-row layout problem (SRLP), double-row layout problem (DRLP), parallel-row layout problem (PRLP), multi-row layout problem, loop-layout problem (LLP), open field layout problem (OFLP), and multi-floor layout problem (MFLP).

The study by Telek and Cservenák (2019) provides a comprehensive analysis and research related to the field of material handling, focusing on different types of material handling. The literature review explores material handling equipment (MHE) including conveyors, cranes, and Automated Guided Vehicles (AGVs). It categorizes the planning methods used for different equipment types: traditional approaches are common for cranes and conveyors, while

AGVs employ advanced methods such as simulation and optimization. The review identifies a research gap in integrating multiple handling tasks and equipment types, suggesting a need for further exploration of comprehensive planning concepts to address the complexities of modern manufacturing systems. Limitations in designing material handling systems are discussed by Mohsen and Hassan (2010), including constraints such as the limited number of equipment options and the simplifications in mathematical models. These limitations can affect cost minimization and efficiency. Effective design should consider objectives like safety, ergonomics, productivity, and equipment utilization while also addressing user requirements such as environmental conditions and system lifecycle.

3.1. Classification and Characterization of Material Handling Equipment:

Classification is crucial in the design process for formalizing solutions in material handling systems. Various studies emphasize the significance of classification frameworks in identifying equipment attributes and challenges. According to Mohsen and Hassan (2010), MHE can be classified into categories such as transfer equipment, support equipment, unit load equipment, and identification and communication equipment. Transfer equipment includes conveyors, AGVs, lifts, and trucks; support equipment encompasses pallet racks and vertical storage systems; unit load equipment involves pallets, totes, and pins; and identification and communication equipment includes printers, scanners, and terminals.

a) Classification Frameworks: Frameworks are important for organizing MHE and identifying patterns, trends, and knowledge gaps. According to the study by Mohsen and Hassan (2010), attributes such as carrying capacity, speed, and lifting altitude and their impact on system cost and efficiency are key to the classification. Functional and technological classifications can be inferred from these frameworks, focusing on equipment attributes and types.

b) Taxonomy Development: Research on taxonomy development in MHE systems is reviewed in García-Cáceres, Torres-Hernández, and Delgado-Tobón (2022). This study discusses the construction of a taxonomy that meets the needs of distribution centers and suggests future research on integrating decision-support systems with expert systems and multi-criteria decision-making approaches like Stochastic Multi-criteria Acceptability Analysis (SMAA) to improve equipment assessment and selection.

c) Characterization Metrics: Performance metrics are essential for evaluating the effectiveness of MHE. The study by Putra, Ridwan, and Astuti (2019) reviews various metrics, including Overall Equipment Effectiveness (OEE), Overall Throughput Effectiveness (OTE Th), Overall Transportation Effectiveness (OTE Tr), and productivity ratios, underscoring the need for comprehensive performance evaluation.

3.2. Identification, Categorization, and Comparison of Material Handling Selection Methodologies and Techniques

a) Material Handling Equipment Levels and Criteria:According to Saputro, Masudin, and Rouyendegh (2015), the selection process of material handling equipment (MHE) is critical as it involves considering and satisfying various requirements, which can be time-consuming and effort-intensive. MHE selection is classified into three levels: high-level, intermediate-level, and low-level methodologies. High-level selection focuses on choosing suitable MHE categories, intermediate-level on selecting appropriate types within a category, and low-level on selecting specific MHE within a type. High-level problems have fewer diverse alternatives, while low-level problems are more complex due to the many possible alternatives. Intermediate-level selection is divided into:

- **Within-Groups Alternative Selection**: This focuses on selecting specific MHE types within a category. The diversity of equipment can complicate the selection. For example, initially considering an industrial truck might lead to choosing the most suitable type like an E-counterbalanced truck.

- **Specific-Group Alternative Selection**: This is simpler than within-group selection, focusing on finding the most appropriate type of MHE within a specified category. For example, selecting the best industrial truck among IC-counterbalanced, E-counterbalanced, narrow aisle, and E-pallet trucks.

In Figure 2, the MH equipment is grouped into three types:

- Higher level MHE selection (Among categories) that involves evaluating different equipment options based on some factors like speed, capacity, and cost to determine the most suitable solution for a specific operational need. It requires comparison through different method such as MCDM and AHP.
- Middle level selection problem (Within category) that select MHE from the similar category based on specific performance criteria. It focuses on ideal objects within a defied group to meet operational requirements.
- Lower level selection problem (Within a type) that involves the comparison of different models, configuration of the same equipment to find the most efficient and cost-effective option to meet operational requireme

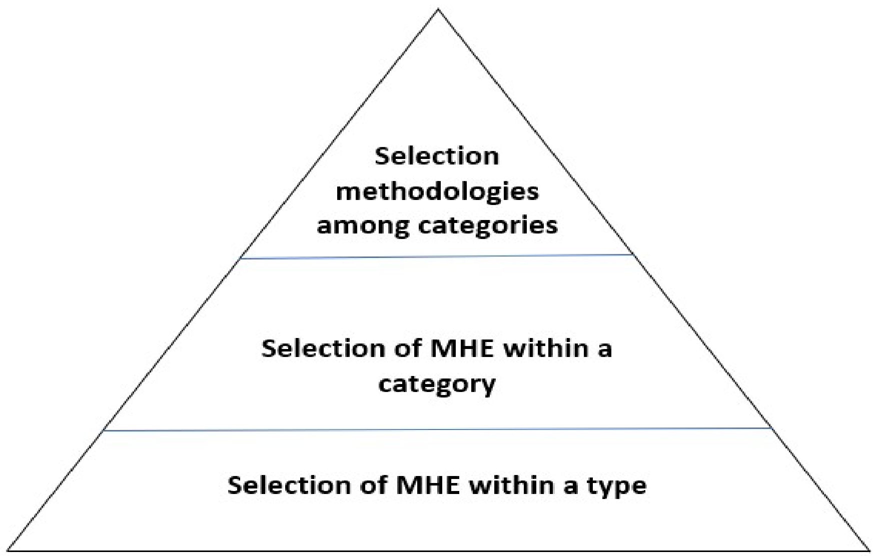

Figure 2. Material Handling Equipment selection levels

b) Problems of selecting material handling equipment: According to Saputro, Masudin, and Rouyendegh (2015), MHE selection problems can be grouped into three contexts:

- **Multi-Criteria Selection Problem**: This involves assessing alternatives based on various criteria such as material, movement, and method. The decision-making process relies on intuition, opinion, knowledge, and experience.
- **Multi-Objective Selection Problem**: This involves selecting alternatives based on multiple objectives, ensuring that all objectives are met without compromising others. This approach uses quantifiable data to form objective functions and constraints, often employing linear programming (LP) methods. LP models consist of:

1. Objective function
2. Constraints
3. Decision variables
4. Parameters

The LP methods can be formulated as:

$z = C1x1 + C2x2 + \cdots + Cn$ (Objective function) (1) (Constraints)

$S1x1 + S2x2 + \cdots + xn \leq$ Vehicle capacity (2)

$x1 \geq 10$ units (3)

(Non-negative value)

$x1, x2, x3 \geq 0$ Stevenson, W.J. (2009) (4)

- **Single-Objective Selection Problem**: Focuses on selecting an alternative that satisfies a single goal or objective, simplifying the decision-making process compared to multi-objective problems (Saputro, Masudin, & Rouyendegh, 2015).

c) Approaches for Selecting Material Handling Systems (MHS): Several approaches are used for MHE selection, including multi-criteria decision-making (MCDM), augmented ε-constraint methods, and optimization models. Determining the weight of criteria is crucial in MCDM methods, which include:

- **Objective Weight (Using Entropy Weight Method)**: Ignores subjective judgments and determines weights through mathematical calculations.
- **Subjective Weight (Using Fuzzy AHP Method)**: Relies on decision-makers' considerations or judgments, calculated using methods such as the eigenvector method, weighted least square method, Delphi method, and mathematical programming.

MCDM problems are formulated as a matrix, with weights assigned to describe the relative importance of alternatives. According to Saputro, Masudin, and Rouyendegh (2015), the study also reviews approaches such as artificial intelligence, optimization, and hybrid methods. MCDM approaches are suitable for cases with fewer alternatives, while optimization is crucial for solving assignment problems. The development of hybrid approaches integrating optimization and other methods is recommended to highlight technical and economic feasibility.

3.3. Identification of Available Material Handling Modeling Techniques

Several techniques have been developed to analyze, design, and optimize material handling systems. Previous studies focus on the optimization of material handling equipment, often neglecting modeling and simulation techniques such as Discrete Event Simulation (DES), Agent-Based Modeling (ABM), System Dynamics (SD), and Finite Element Analysis (FEA).

a) **Discrete Event Simulation (DES):** The study by Johnson and Brandeau (1996) highlights the significant increase in the application of DES in manufacturing and material handling. This growth indicates a rising interest in the field, with research shifting from system design to operation planning and scheduling. Emerging trends include real-time control, maintenance operations planning, and simulation optimization. Integrations with neural networks and genetic algorithms are on the rise, offering advantages over traditional approaches. However, more efficient techniques are needed to handle manufacturing complexity and to integrate with management systems for long-term planning. DES is used to model and analyze complex systems characterized by discrete and sequential events, simulating material movement, equipment utilization, and system performance over time. It allows for scenario evaluations under various conditions, such as changes in layout, equipment configurations, or operational policies. In the era of Industry 4.0, integrating DES with Digital Twin (DT) technology can optimize processes in material handling. While DES models evaluate scenarios, DTs use real-time data for enhanced decision-making and predictive maintenance. Research focuses on applying DES and DT to warehouse optimization, order picking, and equipment monitoring, with data integration and scalability representing research gaps (Agalianos, Ponis, Aretoulaki, Plakas, & Efthymiou, 2020).

b) **Agent-based Modeling (ABM):** The study by Bonabeau (2002) defines ABM as a powerful simulation technique used in numerous applications, including flow, organizational, market, and diffusion simulations. ABM offers a computational framework to simulate the behavior of individual agents such as machines, products, raw materials, and labor. The study by Maka, Cupek, and Wierzchanowski (2011) presents a model for warehouse decision-making using ABM to optimize systems involving factors like information flow, loading/unloading time, quality analysis, and error monitoring. ABM is considered a tool for studying interactions between people, things, and time, often using stochastic models built from the bottom up.

c) **System Dynamics (SD):** The study by Sterman (2000) suggests that System Dynamics (SD) is a useful modeling and simulation tool for material handling systems. SD represents complex systems like warehouses, distribution centers, and supply chains, explaining interactions and impacts over time using feedback loops.

d) **Finite Element Analysis (FEA):** The study by Johnson and Brandeau (1996) outlines the capabilities of FEA to model key aspects of warehouse operations, focusing on estimating performance measures (Figure 3).

e) **Optimization Techniques:** Optimization techniques are vital in designing material handling systems. A review by Negahban and Smith (2014) indicates a lack of research in this field, with Figure 3 showing statistics related to optimization techniques in material handling systems often containing irrelevant content. Relevant optimization techniques include Queuing Theory, Genetic Algorithms, and Linear Programming, as discussed in studies by Asef-Vaziri and Laporte (2005), Mak, Wong, and Chan (1998), and Amjath et al. (2023).

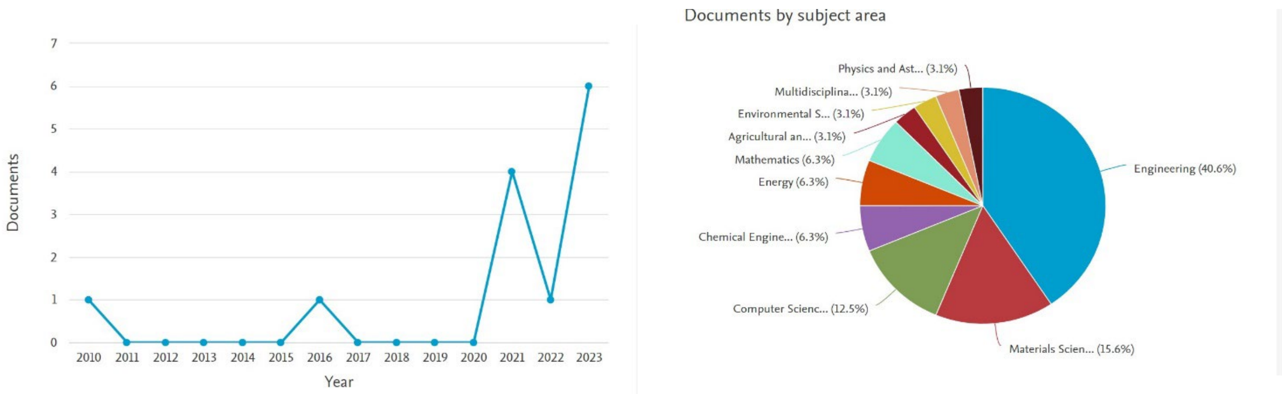

Figure 1. Research statistics on optimization using SCOPUS

4. Results and Discussion

4.1. Literature summary and analytics

The findings from the expanded literature review can be visualized in the Figure 4.

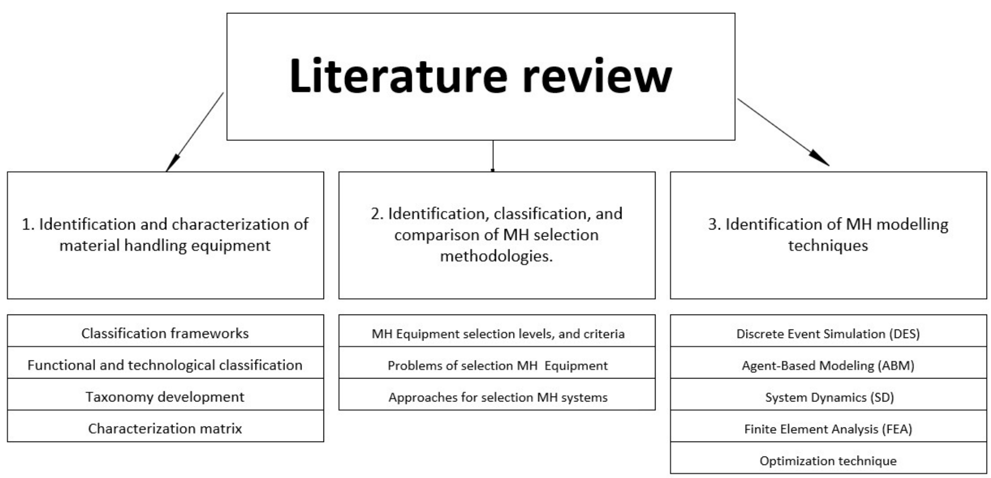

Figure 2. Literature review summary

The exploratory study has reviewed the following MH systems' aspects:

a) MH equipment classification and categorization:

- Reviewing some different classification frameworks that exist for differentiating MH equipment.
- Functional and technological classification is needed to categorize MH equipment and their applications.
- MH equipment taxonomy can be considered a guide for the MH selection process and user requirements.

b) MH equipment selection methodologies and techniques:

- High-level, intermediate-level, and low-level methodologies are involved in MH selection.
- Multi-criteria selection considers various criteria such as move and method. On the other hand, multi-objective selection focuses on satisfying multiple objectives at the same time.

Figure 5 integrates the findings to highlight how selection problems, levels and simulation techniques should be linked to each other. It suggests connecting equipment taxonomy and low-level selection problem which enables a more cohesive framework for MHE selection in the future. There can be also an integration between modeling techniques, selection approaches and the level of selection problems in order to reach an appropriate selection for MHE. This figure also summarizes the outcomes of the literature review with referring to their corresponding references. On the left side of this figures, it shows the three main objectives of this literature review and their corresponding items. In the middle, it shows that the levels of selection represented in a pyramid illustrating the levels. On the right side of this figure, the references are referred corresponding to the numbers in the Figure 5.

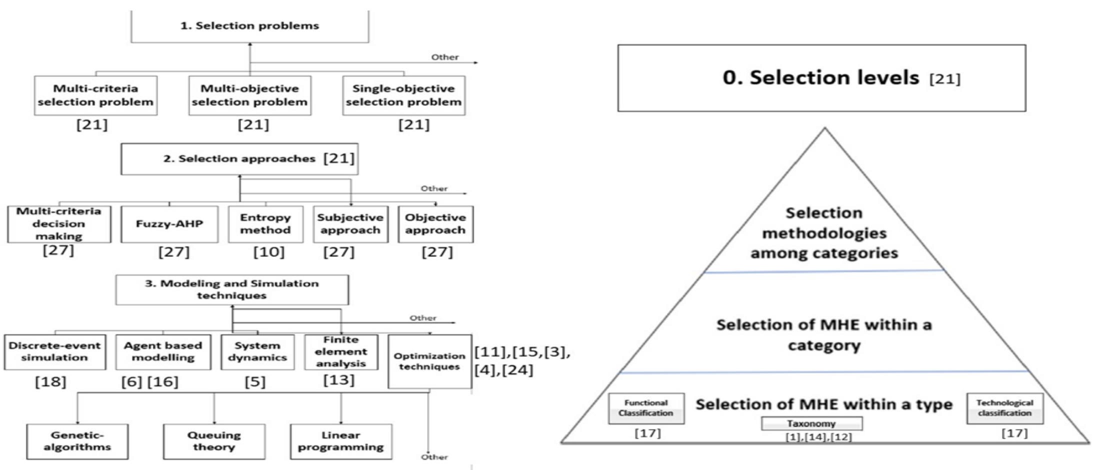

Figure 3. Review summary gathered from studies

(Bouh and Riopel, 2015), (Zoraghi et al., 2013), (Chakraborty and Banik, 2006), (Negahban and Smith, 2014), (Bonabeau, 2002), (Maka et al., 2011), (Sterman, 2000), (Johnson and Brandeau, 1996).(Asef-Vaziri and Laporte, 2005), (Amjath et al., 2023), (Drira et al., 2007), (Kay, 2012), (Mak et al., 1998), (Material Handling Industry, 2024).

4.2. Research gaps

MH equipment selection

- Methodologies solutions are based on elementary techniques and ignoring calculations and computations. As some of the researches depends on heuristic approaches. These approaches may include basic decision rules or straight forward criteria which does not consider complexities.
- There is a research gap in applying lean manufacturing principles as optimization strategies. Lean manufacturing principles aim to eliminate waste as a supporting goal for reaching a balanced rapid flow as an ultimate goal. Techniques such as value stream mapping (VSM) and continuous improvement (Kaizen) and Just in time (JIT) production should be considered.

There is a need for further investigation of planning concepts and decision-support systems to highlight the difficulties. Planning in MH systems includes coordinating multiple variables such as equipment, availability, layout, workflow, and cost management. However, there is a diversity of the review findings regarding MH systems various aspects, the linkage between them can build a standardized model for MH systems. An initial frame work is proposed to plan, design, and analyze MH systems through some actions such as defining the problem, identifying MHS objectives, proposing MHS, evaluating, testing, finalizing and standardizing. Each step is related to the key findings from the literature review, making use of some modeling techniques and approaches shown in table1 and 2 which can help in the modeling and development that should be emphasized using the following:

1. Modeling of material handling equipment and systems
2. Analysis and Design of material handling systems
3. Addressing industrial setups such as Lean manufacturing and Industry 4.0

Despite the varied findings in the review concerning different aspects of material handling (MH) systems, establishing connections among these findings could lead to a standardized model for MH systems. An initial framework is suggested to plan, design, and analyze MH systems, which includes steps like defining the problem, identifying objectives, proposing solutions, evaluating, testing, and finalizing the design. Each of these steps is tied to significant insights from the literature review. This proposed framework can be further developed in future work by integrating it with the selection levels pyramid shown in Figure 2.

4.3. Proposed framework for MHS

A frame work in Table1. is proposed for designing MHSs, which can be considered as a guide or manual for the designing processes. The framework goes into 5 critical stages, and each stage needs some modeling technique or working mechanism to be identified. Defining the problem is the stage of understanding the current state of the material handling systems, and it also includes describing the problems and representing layouts and operations together to analyze strengths and weaknesses of the material handling systems generating some constraints and highlights the area for improvement. In the second stage, the MHS designer should decide a clear measurable objective for MHS and the goals should align with the goals of the facility. Proposing MHS includes selection of new MHE, layouts, modification on existing MH processes in the facility. The fourth stage includes test the feasibility of proposed solutions and needs some modeling tools such as layout, operations, and material handling systems to be identified. In the last stage, which is finalizing and standardizing, it is recommended to make a full detailed plan for the implementation process. By following this framework, we can systematically follow design and analyze material handling systems to achieve optimal MHS solutions (Table 1 and Table 2).

Table 1. Initially proposed framework or methodology related to the findings from Figure 5

	Define the problem	**Identify MHS objectives**	**Propose MHS**	**Evaluate and test**	**Finalize and standardize**
	Represent the current system (Layout and operations)	MHS related objectives to be identified (in connection with the system performance parameters)	Selection of MHE	Simulation/Evaluation/ Analysis	Ensuring the efficiency and the effectiveness of addressing the identified objectives
Modeling	Layout + operations	Objectives	MH Systems	Layout + operations + MH systems =objectives	Layout + operations = MH systems
Approach	Describe	Identify	Propose and evaluate (Iterate When necessary)		Specify

Table 2. Supporting literature review background

	Define the problem	Identify MHS objectives	Propose MHS	Evaluate and test	Finalize and standardize
Relevant Material	[9], [21]	[1], [10], [12], [14], [17], [21]	[1], [10], [12], [14], [17], [21]	[1], [10], [12], [14], [17], [21]	[16], [18], [24]

Drira et al. (2007); Saputro et al. (2015); Material Handling Industry (2024); Saputro and Rouyendegh (2016); Garcìa-Càceres et al. (2022); Kay (2012); Mohsen and Hassan (2010); Maka et al. (2011); Negahban and Smith (2014); Stevenson (2009).

5. Conclusion

This research has gone deep on the various aspects of MHS, exploring their classification, selection methodologies, and modeling techniques. The literature review highlights the critical role of efficient material handling in optimizing facility operational costs. However, there is still a room for exploration, especially in the field of digitalization or lean manufacturing practices regarding the science of material handling.

To sum up, the main objective of this research is to review various aspects of material handling (MH) systems, including the classification and identification of material handling equipment (MHE), comparing selection methodologies and techniques, and identifying available modeling techniques. A comprehensive literature review was conducted, and several findings were gathered, as illustrated in Figures 4 and 5. These findings led to the initialization of the framework presented in Table1, which can guide future research by defining the problem, identifying MHS objectives, proposing MHS solutions, evaluating, testing, finalizing, and standardizing. The future research can focus on integrating digital technologies such as digital twin, AI, or advanced optimization tools to improve the efficiency of MHS. Researches can develop brilliant solutions for real-time monitoring, and supply chain optimization. Future research can contribute to the enhancement of MHS and their positive impact on industrial operations.

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Biographies

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