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► **To cite this version:**

Zakarya Soufi, Pierre David, Zakaria Yahouni. Challenges of Material Handling System design in the context of industry 4.0. 12th international workshop on service oriented, holonic and multi-agent manufacturing systems for industry of the future, Sep 2022, Bucharest, Romania. pp.291-303, 10.1007/978-3-031-24291-5\_23 . hal-03951546

**HAL Id: hal-03951546**

**<https://hal.science/hal-03951546v1>**

Submitted on 23 Jan 2023

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# Challenges of Material Handling System design in the context of industry 4.0

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**Abstract.** Mastering Material Handling Systems is a crucial issue for numerous companies since the costs of Material Handling activities are far from being negligible. The demand for a sustainable industry and the introduction of industry 4.0 technologies for Material Handling are renewing the Material Handling System design concerns. Many questions arise on whether it is suitable or not to bring technologies such as Autonomous Mobile Robots or Real-Time Location Systems to the shop-floors. In the presented study, various companies are questioned on their utilization of new technologies and on their processes to manage and modify their Material Handling System. It appears that practices in Material Handling System design and management are diversified and that no consensus exists on how to efficiently design these systems. A cross-analysis is performed to identify the differences and the common patterns between the literature and the field study. This work discusses the need to better understand the relation between the different aspects of Material Handling System design and presents key challenges to be addressed in the context of industry 4.0. To address these challenges, research directions are proposed. They are composed of four main challenges area: Material handling specifications, Material Handling Equipment selection, Material Handling Equipment deployment, and Material Handling System analysis.

**Keywords:** Material Handling, Material Handling System design, Material Handling Equipment, Level of Automation, Industry 4.0.

## 1. Introduction

Material Handling System (MHS) addresses storing, packaging, and moving products. It plays a key role in the performance of the entire manufacturing system [1,2]. In this article, MHS is considered to be a collection of Material Handling Equipment (MHE) and operators realizing the internal logistics task of a factory. An efficient MHS leads to effective production management, improvement of on-time delivery, and enhancement of production quality [3]. But the MHS could be a source of excessive expenditure if it is not efficiently designed [4]. The design of MHS is renewed by the high amount of newly available technologies coming from Industry 4.0. To cite a few, Autonomous Mobile Robots are proposed along with Real-Time Location Systems (RTLS) or cobots. These technologies are seen by many as a solution to support the

production systems in reaching their goals of operational excellence and agility. Nevertheless, considering the literature MHS design is missing a largely admitted design process that handles the challenges of industry 4.0. The main approaches focus on some MHS sub-problems, such as the optimization of material flow [5], the definition of the appropriate Level of Automation (LoA) [6], or Material Handling Equipment (MHE) Selection Problem [7]. These problems are separately addressed in the literature, which does not allow to solve the MHS design problem with a systemic view. Automation is an important principle in classic MHS design approaches [8,9]. In these approaches, the automation of Material Handling activities is presented as a mandatory path without precisely analyzing the company context. However, many articles support the idea that LoA must be carefully defined to maintain the effectiveness of systems [10]. There is currently no evidence that the MHS design problem is mastered in the industry.

The first contribution of this paper is to analyze some of the existing practices of MHS design in five companies and compare them to the literature. The objective is to identify the potential improvements in the processes, methods, and tools to make the right decision in MHS design projects. The second contribution is to propose research directions organizing the needed improvements in MHS design processes within the context of industry 4.0. The results of the field studies are not to be generalized, but to identify some of the practices that can be found in today's industries. The remaining of this article is organized as follows: It starts with a literature review on Material Handling. Afterward, the field studies are presented through their cross analysis to identify the currently encountered practices for MHS design and management. Finally, based on the obtained results, research challenges for MHS design are discussed. The conclusions are summarized in the last section

## **2. Material Handling System Design**

The design of MHS is studied by many researchers, but no consensus exists on defining an appropriate design process. Namely, differences may be found whether the study addresses a modification of an existing system or the design of a new system. MHS design may be of various complexity: it can address single point-to-point transportation or a whole plant transportation network design. Nevertheless, different approaches may be found in the literature. The approaches are sometimes design principles with associated analysis tools and sometimes optimization-oriented approaches. For instance, in [11] the authors propose an approach that integrates the design of facilities and the MHS to minimize the Material Handling cost. This approach mainly focuses on the layout of the MHS by defining the location of the pick-up/delivery stations and the paths and their associated direction.

In [8,9] the authors cite 10 principles that should be taken into consideration during the design of MHS. These principles are developed by the MHI association ([www.mhi.org](http://www.mhi.org)). The principles to be applied to MHS design are summarized in 10 concepts to consider or define when designing an MHS: Planning, Standardization, Work, Ergonomic, Unit load, Space utilization, System, Automation, Environmental, and Life

cycle cost. The concepts are well defined but not articulated to form a design approach. They just highlight the important points to consider in the design process.

In addition to these 10 concepts, [8] propose to structure the approach to find the right Material Handling solution with five standard questions (Why, What, Where & When, How, Who). It might be noticed that the questions are addressing a single point-to-point movement when a global approach of the whole MHS design should be carried out.

In [12] the authors propose a design approach that is based on the examination of materials and routes. The design approach is composed of four steps: Assemble flow analysis output, Class selection of route, Calculation of requirements, and selection.

In this kind of approach, it is assumed that the plant layout is constant and known. The workstation placement does not change and cannot be changed. And finally, production volume is assumed to be constant. It can be noticed that neither the technology nor the communication and control systems are addressed by this proposal. Important aspects such as the Internal logistics and automation strategies of the company should also be analyzed [13].

Research works highlight the importance of company strategy analysis to correctly address the MHS design. As stated in [9,12], it is essential to associate the competitive advantage or the company's strategy with its MHS design. MHS design should fit and supports the firm's manufacturing strategy [12] and should also reflect the strategic objectives and the needs of the organization [9,13].

The main global design approaches found in the literature give high-level outlines of the process but remain vague on its realization. The proposed principles are to be used but the approaches lack of precision and do not explicitly tackle the new challenges of industry 4.0. The more precise approaches based on optimization algorithms concentrate on sub-problems of MHS design.

To propose complement the vision on MHS design problems, a field study at various companies is conducted to extend the observations made from the literature. The second objective is to analyze if literature results spread in companies. The next section presents the field studies conducted within 5 different industrial companies to share their experience of MHS design, management, and usage.

### **3. Field studies**

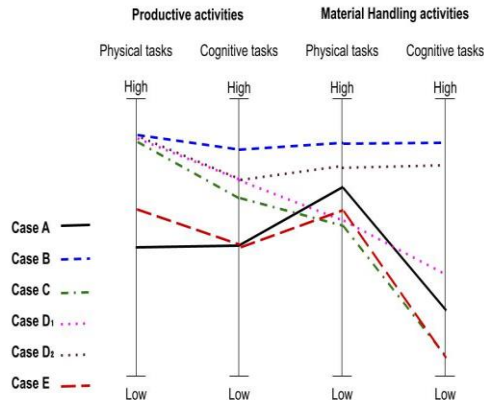
#### **3.1. Field study design**

Five interviews are conducted using a grid analysis. Then three steps are adopted to exploit the data; data reduction, data display, and cross-analysis. This procedure is inspired by the work of Säfsten et al. [14]. Table 1 presents general information about the company typology. Five companies have been chosen to observe different practices. The interviews were semi-directed, with additional questions to deepen the interviewee's answers. In most of the cases, the interviews were complemented by a plant walkthrough.

**Table 1. Cases general information**

Case	Field	Global number of employees	Product size, volume, and complexity	Production strategy	Production organization
Case A	construction machinery manufacturer	102.300	Large, high, complex	Make to order, make to stock, and engineering to order	Assembly line
Case B	Semiconductor manufacturer	45.500	Small items large batches, very high, complex	Make to order	Flexible job shop
Case C	Stainless steel fixings	40	Small, very high, medium	Make to order	Flexible flow shop
Case D	Fastening and assembly solutions	7.250	Small, very high, medium	Make to stock	Flexible flow shop
Case E	Metal wire parts manufacturer	130	Small & Medium, small to medium, simple	Make to order	Job shop

To analyze the companies' practices, questions were asked to understand the MHS Design process and to understand the MHS solutions implemented on sites. To distinguish the various typology of MHS solutions, the different cases are analyzed in terms of LoA. For that purpose, the LoA analysis concept proposed by Parasuraman et al. [15] is adopted. The concept allows visualizing the LoA of different systems through the cognitive and physical aspects. The visualization was originally made through four classes of information functions (information acquisition, information analysis, decision and action selection), and action implementation. In this study, it is used to visualize the LoA of different cases based on two types of activities; Productive activities and Material Handling activities (see figure 1). For each type of activity, the physical tasks and cognitive tasks are analyzed in an aggregated view. Productive and Material Handling activities are analyzed to identify if the automation strategies are different within the company. Figure 1 summarizes the observation made on the visited plant LoA. Due to space limitations within this article, we are not presenting the whole cases description. But a cross-analysis revealing the important facts of analyzed cases is provided in the next section. The purpose is to report on the observed practices and to raise a promising subject for future research on MHS.



**Fig. 1.** Advancement in terms of Automation.

### 3.2. Cross analysis

To identify the main challenges of MHS in the context of the fourth industrial revolution, this cross-analysis is based on four axes; Material Handling Automation, Material Handling Control System (MHCS), MHE Selection, and MHS design. The analysis of each axis starts with a review of practices of the different cases. Then, common and different patterns are highlighted. Besides, when needed, the literature is mentioned to compare the theoretical and the empirical materials. A summary of the cross-analysis is presented at the end of this section opening new research questions.

#### 3.2.1. Material Handling and Automation

As it is shown in figure 1, the gap between the automation of physical tasks and cognitive tasks in Productive activities is not as significant as in Material Handling activities. The automation of Material Handling is more restrained compared to the automation of productive activities. Sometimes this restriction is driven by the corporate culture of the company. On one hand, the small and medium-sized companies (such as cases C and E) tend to automate the Productive activities more than the Material Handling activities. On the other hand, the large-sized companies (such as cases B and D) aim to adopt high LoA for both Productive and Material Handling activities. Besides, in terms of Material Handling activities, the physical tasks are more automated than cognitive tasks. In 4 cases (A, C, D1, E), decisions related to the cognitive tasks were left to the human, e.g. parts positioning, storing, navigation, and so on. Although the LoA of cognitive tasks of Material Handling activities is low compared to others, several companies tried to test new technologies that offer higher LoA for cognitive tasks. E.g. both cases B and D tried to deploy AIV in their plants, which offers a high LoA for both physical (e.g. moving) and cognitive tasks (e.g. navigating through the plant). The use of this equipment was accepted by case D, and rejected by case B due to many factors (behavior unpredictability, collision risks, etc.). The choice of the appropriate LoA seems to be difficult to make. Automating the cognitive Material Handling actions

seems to be linked to the intensity of the product flow (such as in cases B and D2 where the flow must be kept at its maximum to satisfy the demand). While the automation of the physical Material Handling actions appears to be related to the characteristics of the handled materials (as in case A where the handled materials are heavy and require high physical automation). However, a thorough study has to be done to identify other parameters that might influence decisions related to LoA. Additionally, methods can be found in the literature for the readjustment of LoA such as DYNAMO ++ [6]. The procedure of DYNAMO ++ can be applied for existing MHS only. Yet no methods can be found in the literature to assist the LoA decision for a new MHS. Based on the results shown above, it is shown that, although automation is considered a crucial element of the MHS design, the LoA definition remains unclear. Thorough studies have to be conducted to identify parameters and propose procedures to support the choice of LoA for the design of MHS.

### **3.2.2. Material Handling Control System**

The field studies show that the use of technologies related to the MHCS is heterogeneous. For some cases, the investment in such technologies is not needed since the used MHE do not have a significant cognitive LoA (e.g. pallet trucks). But for other cases, it is important to deploy this kind of technology. In case B, the use of such technologies is mandatory due to the high LoA adopted in the plant. In case D, recent tests were done to include this type of technology. The MHCS in this case allows the operators to control, program, and supervise the AIVs through a screen. The investments in different cases are mainly driven by two factors; the need to remove Non-Value Added (NVA) activities and to have an ROI in a short period. To present convincing proofs, simulation has to be done to display the possible benefits that can be derived from the use of such technologies. In the literature, several structures and technologies related to the MHCS can be found. While in the field studies, it can be seen that MHCS technologies are slowly emerging for large-sized companies. On the other hand, the MHCS is still not considered by small and medium-sized companies. Consequently, it can be seen that MHCS is not widely used, and the implementation of such technologies remains unclear in the literature. More research has to be done to develop this subject and propose methodologies for the deployment of MHCS.

### **3.2.3. Material Handling Equipment Selection.**

Throughout the field studies, it is noticeable that investment for developed MHE is not simply related to the size of the company nor the complexity and the size of the production. Even small-sized companies such as case E, with a small and medium production volume, are using equipment such as cobots. The selection of this equipment is mainly done through benchmark with a restrained list of suppliers, this practice is sometimes successful (e.g. the selection of the tugger train in case A). However, it does not always ensure positive results, e.g. in case C, the selection of an automated transfer cart was based on copying the practices of another plant, but appeared not to be suitable. The loading/unloading operations were too difficult to be performed by the operators which negatively impacted the performance of the plant. The criteria used for the MHE

selection in the small and medium-sized companies are limited and mainly focus on economics. Furthermore, the large-sized companies include diversified criteria during their MHE selection (see table 2). It may be observed that no clear MHE selection method is shared between cases. The decision is often not formalized and is made with a partial view of the impacts on the production system.

**Table 2.** Identified criteria for the MHE selection

Categories	Criteria	Cases
Economical	Return on investment (ROI)	A, B, C, D, E
	The total cost of ownership (TCO)	D
	Cost of the implementation	E
	Cost of the equipment	E
Technical	The capacity of the equipment	A
	Speed movement	A
	Safety	B
Operational	Precision	B
	Operating skills	A
	Ease of implementation	E
Supplier	Supplier's reputation	D, E
	Supplier's location	D, E

### 3.2.4. Material Handling System design

The cases show that companies do not always use a clear method to design their MHS. Large-sized companies (case A, B, and D) use approaches based on benchmarks and on copying the best practices. In addition, case A uses corporate guidelines common for all production sites. These guidelines are principles to apply (e.g. the reduction of the number of part touch) but do not constitute a design process. It is noticeable that in these cases, MHS design is associated with the competitive priorities in a way to fit and support the manufacturing strategy followed by the company (e.g. in case A, the MHS is designed in a way to reduce the number of part touch which positively impacts the OTD). Key Performance Indicators (KPIs) are used to constantly evaluate the system (see table 3). A failure in one of these KPIs triggers the modification of some elements of the design e.g. in case A, an MHE was dropped off because its speed movement and reactivity caused a decrease in the OEE of the line. The small and medium-sized companies (case C and E) do not use any approach for the design process of MHS. Material Handling is not considered as important as productive activities. However, the interviewees were aware of the benefits that could be generated by relevant MHS. E.g. In case E, the use of cobots for simple pick and place activities resulted in removing the NVA activities performed by operators. In cases A and D, the MHS is designed as a part of the production, while for cases B, C, and E the MHS is designed after the production system design. In this context, the MHS design has been adapted to the workshop configuration. In case A, the organization is an assembly line where moving and gathering parts is an important part of the activity. In case D, flow management was seen as an important priority by the top management. It can be noticed that both



companies operate in the automotive market and then share a comparable approach for flow management. With this example, it is seen that the field of production can have an impact on the approach followed for the MHS design. For case B, the management assumes that MHS should adapt to production since growth management and technical factors already constrained production organization. For cases C and E the MHS has not been seen as a high priority. The MHS design process followed in the different cases is mainly done through MHE Selection. Nevertheless, the literature shows other potential factors (e.g. the LoA definition) that have to be included during the design of MHS. These factors do not seem to be a major concern for the interviewed industrial cases, especially for the small and mid-sized enterprises. These results support the assumptions that the design of MHS still requires a holistic approach that;

- Considers the challenges of industry 4.0.
- Adapts to different industrial typologies.

**Table 3.** Key performance indicators for the evaluation of MHS

Indicators	Cases
Overall Equipment Effectiveness (OEE)	A, B
Non-Value Added (NVA) activities	C, E
Inventory on location	A
On-time deliveries	A
Number of touches	A
Line balance	A
Number of transports	B
Duration of transport	B
Throughput	B
Availability of operators	C
Intermediate storage time	D
Cost of work-in-progress (WIP)	D
Cycle time	D

#### **4. MHS design challenges in the context of industry 4.0**

The theoretical and empirical materials show that the design of the MHS is lacking a global design approach which includes the challenges of industry 4.0. In the literature, MHS problems are addressed as independent problems and are solved separately due to their complexity (e.g. MHE selection, LoA definition, communication structures proposal for the MHS). While the analysis of the literature and the results of the field studies show that the MHS aspects are interdependent and should be treated based on a holistic approach. On one hand, theoretical materials unveil several challenges that can be faced during the MHS design. Therefore, it is important to have a global approach addressing all MHS problems and challenges. On the other hand, the empirical materials display various practices and insights about the different MHS design errors that were encountered (e.g. investments on inappropriate MHE, lack of a design approach,

etc.). In figure 2 the relevant topics to be addressed in an MHS design process are categorized. As a guideline to list research challenges on MHS, we propose changing the paradigm of MHS design by adopting a Systems Engineering approach. MHS design is a complex system design and therefore deserves a well-established design process to be carried out. IEC 15288 [16] proposes efficient guidelines to address such systems development. An MHS design process should take inspiration from such design approaches. It will encourage high-quality specification, stakeholder integration, rationalized design and selection choices, and a well-prepared deployment phase. In the remaining of this section, we will discuss some important research directions linked to the various systems engineering phases.

#### **4.1. Material Handling needs specification**

The field studies illustrate the magnitude of the decisions related to the MHS, it can be fortunate (e.g. the use of cobots in case E) and it can also be deceiving (e.g. the use of the automated transfer cart in case C). This type of problem can be caused by a lack of problem specification including Material Handling need definition and constraints elicitation. The study shows that MHS design decisions are multi-facet and influenced by multiple aspects (e.g. Costs, staff skills, production requirements, to cite a few). An efficient MHS design process should carefully assist designers to precisely specify the MHS design problem [17]. In the literature, techniques for the Material Handling specifications can be found. They consist of charts and diagrams [9] which can be time-consuming and less efficient with the requirements of industry 4.0. New methods are needed to specify the Material Handling activities in a non-technological way, to specify the expected overall production flow, to specify the companies' strategies in terms of internal logistics and admissible LoA, to specify the available deployment, and support systems. A precise company's strategies definition is important as well; Granlund and Säfsten et al. [13,14] show the importance of the analysis of companies' strategies on automation and internal logistics for MHS automation systems. In their work, only automation is highlighted but the authors give relevant advice on these strategies' decomposition.

#### **4.2. MHS architecture definition**

Subsequently to the need clarification comes the design phase of the MHS. In a Systems Engineering process, the purpose is to generate several possible architectures to advance concurrent ideas. The MHS architecture is a composition of interacting MHE and operators, where each element is allocated for a specific set of Material Handling activities. In the field studies, the different cases show a lack of a formalized approach; many cases were using benchmarks or were testing technologies individually. In the literature, general principles are given for the proposal of MHS architectures without sequencing the analysis nor giving procedures to generate sufficient architecture possibilities. However, the literature addresses some MHS sub-problems that should be combined to define a procedure for MHS architecture definition (e.g. the layout definition, the selection of MHE, the MHCS definition, the operational strategy selection, equip-

ment allocation to task, dispatching rules...). The literature shows that, despite the increasing use of IA and computational models to solve MHS sub-problems, the expert's knowledge still remains necessary for such decisions. E.g. current MHE fleet sizing algorithms are always underestimating the number of equipment to use since they omit many constraints as traffic or product availability uncertainty. The empirical and theoretical materials emphasize the need to propose techniques for MHS architecture definition, while including several aspects such as:

- Considering diverse MHE technologies
- Handling task allocation and dispatching rules
- Ensuring a wide search of solution (handling the combinatorial)
- Considering the human/machine interactions
- Considering the needed communication information system
- Considering the experts' knowledge
- Handling criteria related to the company strategies

#### **4.3. MHS performance analysis**

An efficient MHS architecture is dependent on the capacity to analyze foreseen system performances. The analysis of MHS is facing new challenges due to their complexity that follows industry 4.0 trends. Two types of complexity are to be handled for a relevant performance analysis: (1) The complexification of the MHS makes it difficult to predict every emergent behavior coming up from the equipment interaction. Therefore, there is an emerging need to develop performance analysis techniques. These techniques should include the various MHE type and their interactions through communication systems and with onsite operators. The influence of the MHS on the production site behavior including degraded situation is also to be included. This imposes using heavy performance analysis techniques as for Case B and open new research trend in finding techniques to automate evaluation models' creation. (2) The second complexification to handle is the evolving definition of performance for MHS. With current megatrends on sustainability or ethical concerns, the performance cannot be seen through the reduced prism of operational excellence as encountered in most of field studies. New indicators are to be thought to embrace more long-term perspectives as MHS flexibility or sociological aspects as the influence of the MHS on the work group organization.

#### **4.4. MHS Selection**

The selection of the appropriate MHS for a given Material Handling need is not straightforward. The process must be formalized and must involve many dissimilar criteria. The field studies analysis has shown that the selection process is poorly defined for most of the studied companies. Only a few criteria are used objectively or unconsciously by companies and their selection remains unclear. It is not obvious to understand why certain criteria are retained and others ignored. An analysis of literature on MHE [18] revealed that more than 200 criteria were identified for MHE selection processes. While in the field studies of this work, 12 distinct criteria were identified, and the companies used at most 6 criteria to decide. In [18], a methodology with a list of

potential criteria is presented for two analysis levels: MHE category selection and MHE model selection. To advance the field it would be relevant to propose techniques for the selection of relevant criteria, based on the company's characteristics and its industrial activity and strategy.

#### **4.5. MHS Deployment**

The integration of MHS into a plant appears to be challenging due to the high complexity of today's industrial systems. It can be confronted with important problems as the integration to the information system, MHE/Operator interaction or technologically advanced equipment maintenance management. Few works can be found on the integration of MHE to the information system. Wang et al. [19] propose an architecture of Cyber-Physical System (CPS) for MH. The paper shows the potential of such technologies to improve shop-floor production fluency and efficiency. This topic still requires more effort to define other potential technologies that can be used in the context of MH. The interviewed companies expressed their current fear for MHE integration in an MHCS. The deployment of ERP (Enterprise resource planning) or MES (Manufacturing Execution System) in small and medium-sized companies is considered to be a period of intensive work. Therefore, the integration of MHE into a communication network is often feared. The interaction between MHE and the operators should be carefully considered for a successful deployment. As encountered in case E, the company staff may be reluctant to share the workspace with automated systems. In this context, new questions and opportunities about human-machine cooperation arise. The extent of the interventions that should be made by the operators is to be analyzed. Human-Machine Cooperation principles in a manufacturing system context are proposed in Pa-caux-Lemoine et al. [20]. These principles should be adapted to the context of MHS.

### **5. Conclusion**

The objective of this paper is to analyze the existing practices of the MHS design in the literature and five companies to identify the main challenges that are faced in the context of industry 4.0. These challenges may allow researchers to extend their MHS design approaches while including the latest technologies of industry 4.0. The literature review shows that fractions of MHS design problems are solved separately. Meanwhile, in the field studies, it has been shown that there is a lack of a formal MHS design approach. However, some existing practices are used and highlighted in this work, as benchmarking. These practices do not have constant outcomes. It has been shown that sometimes, these practices led to a significant financial loss. The comparisons and analysis stressed the need of having a properly detailed methodology for MHS design that tackles diverse sub-problems. Such a global approach should enhance the use and efficiency of MHS. Moreover, the need to enhance MHS design methodology is increasing with the arrival of industry 4.0 demands and technologies. It has been shown that the deployment of communicating and automatized MHE is difficult for many companies. To address this issue, both theoretical and empirical materials were analyzed based on five Material Handling aspects; Material Handling activities, Material Handling and

Automation, MHCS, MHE selection, and MHS. As a result, MHS design research directions are proposed. For future development, a thorough analysis of each aspect of the MHS design challenge is to be done. For this purpose, techniques for data collection and specification have to be whether identified from the literature or developed. Model Driven approach could be adapted to propose a generic framework to regroup complementing views on MHS. Such framework should rely on an MHS domain metamodel that could enhance data viewing, comparison, and translation to adapted analysis models such as discrete event simulation that could enhance deep MHS analysis.

### Acknowledgments

The authors thank the French National Research Agency (ANR) that funded this research under the LADTOP project (grant ANR-19-CE10-0010-01). The authors would also like to thank the industrial companies for their participation in the field studies.

### References

- [1] B. Esmailian, S. Behdad, B. Wang, The evolution and future of manufacturing: A review, *J. Manuf. Syst.* 39 (2016) 79–100.
- [2] B.M. Beamon, Performance, reliability, and performability of material handling systems, *Int. J. Prod. Res.* 36 (1998) 377–393.
- [3] J.R. Montoya-Torres, A literature survey on the design approaches and operational issues of automated wafer-transport systems for wafer fabs, *Prod. Plan. Control.* 17 (2006) 648–663.
- [4] M.A. Bouh, D. Riopel, Material handling equipment selection: New classifications of equipments and attributes, *Proc. 2015 Int. Conf. Ind. Eng. Syst. Manag. IEEE IESM 2015.* (2016) 461–468.
- [5] J. MacGregor Smith, Queuing Network Models of Material Handling and Transportation Systems, in: *Handb. Stoch. Model. Anal. Manuf. Syst. Oper.*, 2013: pp. 249–285.
- [6] P. Choe, J.D. Tew, S. Tong, Effect of cognitive automation in a material handling system on manufacturing flexibility, *Int. J. Prod. Econ.* 170 (2015) 891–899. <https://doi.org/10.1016/j.ijpe.2015.01.018>.
- [7] T.E. Saputro, I. Masudin, B.D. Rouyendegh, A literature review on MHE selection problem: Levels, contexts, and approaches, *Int. J. Prod. Res.* 53 (2015) 5139–5152.
- [8] S.S. Heragu, Material handling, in: *Facil. Des. Fourth Ed.*, CRC Press, 2016.
- [9] F.E. Stephens, M. P., & Meyers, Material Handling, in: *Manuf. Facil. Des. Mater. Handl.*, Purdue University Press, 2013.
- [10] V. Granell, J. Frohm, M. Winroth, Controlling levels of automation - A model for identifying manufacturing parameters, *IFAC Proc. Vol. 9* (2006) 65–70.
- [11] G. Aiello, M. Enea, G. Galante, An integrated approach to the facilities and material handling system design, *Int. J. Prod. Res.* 40 (2002) 4007–4017.
- [12] R. Shell, E. Hall, W. Wrennall, H. Tuttle, *Material Handling and Storage Systems*, *Handb. Ind. Autom.* (2000).
- [13] A. Granlund, FACILITATING AUTOMATION DEVELOPMENT IN INTERNAL LOGISTICS SYSTEMS, 2014.
- [14] K. Säfsten, M. Winroth, J. Stahre, The content and process of automation strategies, 110 (2007) 25–38.
- [15] R. Parasuraman, T.B. Sheridan, C.D. Wickens, A model for types and levels of human interaction with automation, *IEEE Trans. Syst. Man, Cybern. Part A Systems Humans.* 30 (2000) 286–297.
- [16] International Electrotechnical Commission. International Organization for Standardization, No Title, 2009.
- [17] J.S. Noble, J.M.A. Tanchoco, A framework for material handling system design justification, *Int. J. Prod. Res.* 31 (1993) 81–106.
- [18] Z. Soufi, P. David, Z. Yahouni, A methodology for the selection of Material Handling Equipment in manufacturing systems, *IFAC-PapersOnLine.* 54 (2021) 122–127.
- [19] W. Wang, Y. Zhang, R.Y. Zhong, A proactive material handling method for CPS enabled shop-floor, *Robot. Comput. Integr. Manuf.* 61 (2020) 101849.
- [20] M.P. Pacaux-Lemoine, D. Trentesaux, G. Zambrano Rey, P. Millot, Designing intelligent manufacturing systems through Human-Machine Cooperation principles: A human-centered approach, *Comput. Ind. Eng.* 111 (2017) 581–595.