Movable Factory - A Systematic Literature Review of Concepts, Requirements, Applications, and Gaps

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Abstract

The ability to move production between different geographical locations has recently become more important, due to the increasing need for sustainability and faster response times, complying with local regulations, and dealing with brittle international supply chains. To this end, the movable factory concept has been put forward, which is defined as mobile production units that can be installed near the customer's location. Unfortunately, industrial paradigms such as Industry 4.0 make little if any notice of movable factories but instead focus on the digitalization of their fixed counterparts. In the form of a systematic literature review, this paper breaks down the concept of the movable factory, relates it to the state-of-the-art, and summarizes its main use cases, requirements, research gaps, and opportunities. The review covers over 100 relevant articles published in the past two decades. Compared to existing surveys, we have not only focused on the motivations for movable factories, but also identified research gaps and discuss the impact of modern technologies such as Internet-of-Things, digital twins, and modeling and simulation in fulfilling these gaps. The result is a survey of the state-of-the-art and a list of domains for potential future research on different aspects of movable factories.

Keywords: Automation, Factory-in-a-Box, Industry 4.0, Industry 5.0, Location Independent Manufacturing, Mobile Factory, Mobile Manufacturing System, Movable Factory, Pop-up Factory, Reconfigurable Manufacturing Systems

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Nomenclature

AI	Artificial Intelligence
AR	Augmented Reality
CapEx	Capital Expenditure
DLT	Distributed Ledger Technology
DMS	Dedicated Manufacturing System
DPS	Distributed Production System
DT	Digital Twin
ETO	Engineer-To-Order
FiaB	Factory-in-a-Box
FMS	Flexible Manufacturing System
GPN	Global Production Network
IoT	Internet-of-Things
JiT	Just-in-Time
LIM	Location Independent Manufacturing
M&S	Modeling and Simulation
MMS	Mobile Manufacturing System
MPS	Modular Production System
OPEX	Operational Expenditure
RMS	Reconfigurable Manufacturing System
SME	Small and Medium-sized Enterprises
TRL	Technology Readiness Level
VR	Virtual Reality

1. Introduction

To maintain competitiveness in the global market, manufacturing companies need to reduce production costs while keeping up with the high quality and short delivery time of the products [1]. However, these can be undesirably challenged by uncertainties in the supply chain [2], variations in the products [3], changes in customer requirements [4], local regulations [5], etc. A particularly important factor is transportation prices. A recent study reports a steep increase of 180% in the global shipping prices in the period from November 2020 to February 2021 primarily as a result of Covid-19 [6]. The increased shipping distances as a result of the globalized market [7] and the increased size of the products will further challenge the cost and time constraints in manufacturing. Likewise, the transportation feasibility sometimes puts constraints on the size and weight of the manufacturing products [8], such as in the case of the wind turbine blades, nacelles, or towers. In addition, permission from authorities must be acquired before the transportation of the bulky wind turbine components, which is also a time-consuming task. Moreover, some customers and local/international regulations demand specific environmental practices that manufacturing companies need to take into account to meet climate and sustainability requirements [9, 10]. A new manufacturing paradigm is needed to address these challenges.

A recent manufacturing concept is to move the production sites closer to the location of the demand. This emerging concept that has recently been adopted by some manufacturing companies (see examples in Section 4) is known as a movable factory. A movable factory is composed of mobile manufacturing modules that are easy to transport to different production sites, can be quickly assembled to form a complete manufacturing process, and can be easily reconfigured to meet requirements for change drivers such as new types of products and technologies, new production volumes, supply chain variations, local regulations, etc. In addition to addressing the manufacturing challenges regarding time, cost, and sustainability, a movable factory can create a high degree of internal flexibility, responsiveness, as well as the capability of operational reconfigurability to suit new demands. Furthermore, the movable factory concept facilitates localization of the production/manufacturing [11], which offers several advantages such as (1) job creation to boost the local economy, (2) emission reduction by reducing the transportation needs and long-distance shipping, and (3) overall cost savings by avoiding import duties or shipping expenses. The motivations and

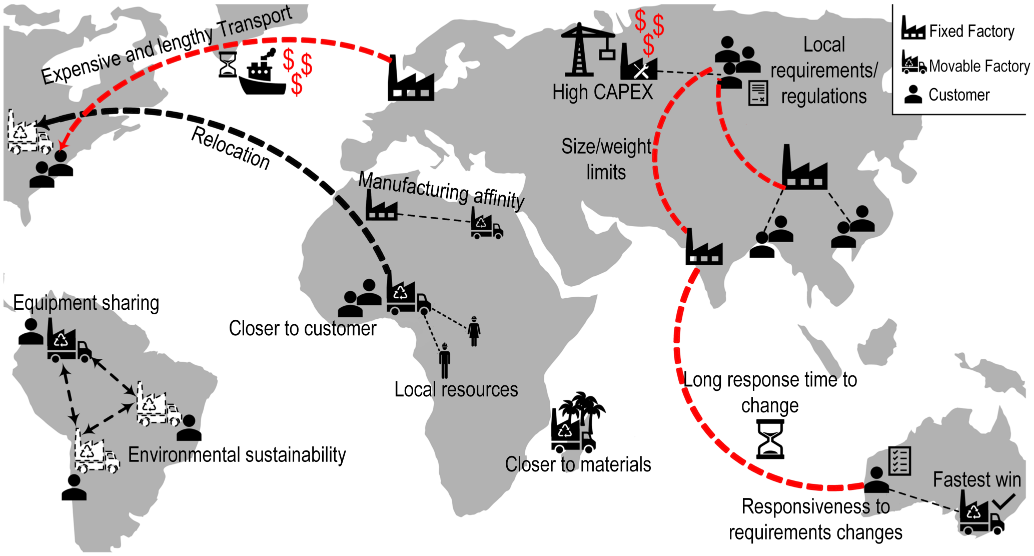


Fig. 1. Illustration of the main motivations and benefits of the movable factory versus a fixed factory.

benefits of mobile manufacturing are conceptually depicted in Fig. 1.

Based on a systematic literature review, this paper discusses the concept of a movable factory also referred to as a Mobile Manufacturing System (MMS). The aim is to provide a holistic overview of the benefits and challenges, characteristics, requirements, applications and use cases, and to provide guidelines for when to use an MMS instead of fixed factories, and suggest areas of future research. Until now, the research on the MMSs has been scattered under several different names, such as MMS [12], Movable Factory [13], On-site factory [14], Factory-in-a-Box (FiaB) [15], and Location Independent Manufacturing (LIM) [16]. While these concepts have some differences, they all share the same main characteristic, that is, the ability to geographically move the manufacturing system from one place to another. Furthermore, no previous effort has been devoted to reviewing the MMS concept by systematically examining all scientific publications. However, there have been several non-systematic overviews including [16, 17, 18, 19] to describe the concept of the MMS. Some reviews such as [14, 20, 21] have focused on the use of movable on-site factories in the construction industry. In these reviews, the on-site factories are considered beneficial to achieve automated, scalable, and distributed manufacturing systems in the construction sector. Lastly, studies in [22, 23, 24, 25] have investigated the use of small low-cost MMSs for sustainable manufacturing in areas where people lack manufacturing skills and the necessary infrastructure for large fixed factories. However, the challenges and benefits in these areas are not all the same as large modern companies are concerned with. This review covers the aforementioned gaps by comprehensively discussing the definitions, benefits and challenges, applications, and requirements of movable factories.

The review is organized as follows: Section 2 describes the review methodology and the literature analysis. In Section 3, the life cycle of the movable factory is presented and in-depth discussions regarding the background, definitions, benefits, and relevant manufacturing concepts are included. The taxonomy, use case analysis, and requirements of the movable factories are covered under Section 4. The main challenges and identified research opportunities are presented in Section 5. Finally, Section 6 concludes the paper.

2. Methodology and Literature Analysis

A systematic approach is selected to carry out the literature review on the MMS topic following the methodology laid out in [26]. As shown in the flowchart of Fig. 2, the review method consists of four main stages, namely (1) planning, (2) screening and reading, (3) analysis and discussion, and (4) documentation. In the following, different stages are explained in detail. The first step was related to the planning in which the relevant keywords and search databases were selected. The search settings and paper screening summary are listed in Table 1. In the search process, different publication types including peer-reviewed articles, book chapters, dissertations/theses, and technical reports were considered. All documents published since 2000 were considered. The search was fulfilled considering well-established scientific databases including Scopus and IEEE Xplore in addition to the grey literature which was found through Google Scholar search. Overall, 23 keywords were considered as search strings, as listed in Table 1. The keywords were obtained by preliminary exploring of related papers in dialogue with industrial experts. In the second stage, the validity and relevance of the articles were preliminarily checked using an iterative approach, in which we first screened the titles of the papers and accordingly removed non-relevant items. Many of the articles could not be judged by their titles alone. These articles were assessed in the second iteration by screening their abstracts. Some other articles were also added to the literature review database using

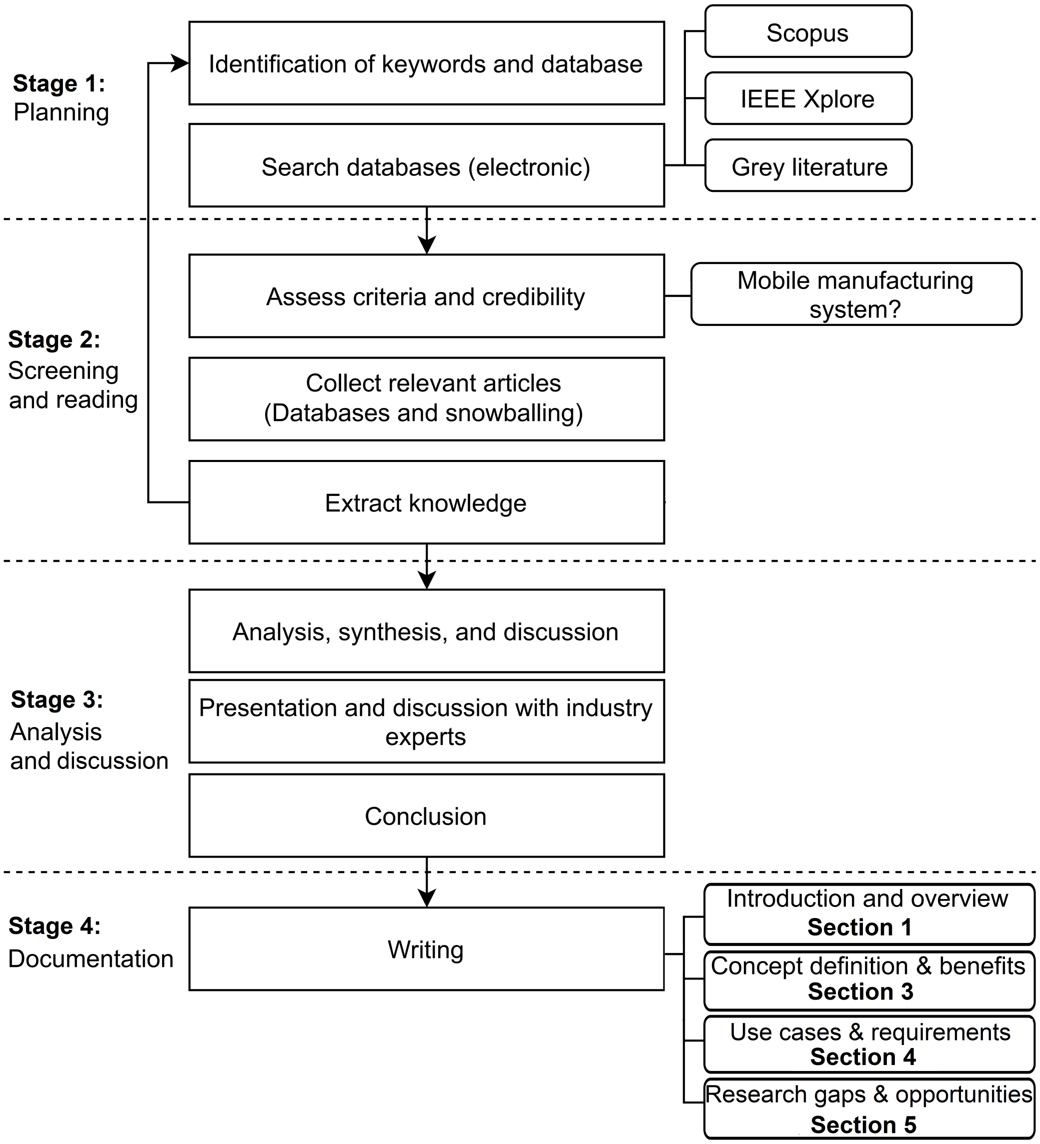


Fig. 2. Flowchart of the methodology used for the literature review.

the snowballing technique, in which the reference lists of the articles found were scanned for new sources and subsequently, the iterative search process was applied again to find additional relevant articles. The applied method resulted in overall 105 articles to create the final literature review database. It should be noted that only the literature in English was considered. Af-

Table 1
Search settings and paper screening summary.

Searching Index	**Specific Content**
Database	Scopus, Grey literature, IEEE Xplore
Publication type	Peer-reviewed journal and conference articles, book chapters, technical reports, dissertations/theses
Search string	"movable factory", "movable factories", "moveable factory", "moveable factories", "portable factory", "portable factories", "transportable factory", "transportable factories", "factory-in-a-box", "factory in a container", "location independent manufacturing", "on-site factory", "pop-up factory", "mobile factory", "mobile factories", "mobile manufacturing", "mobile production unit", "movable production", "moveable production", "reconfigurable production", "reconfigurable manufacturing", "mobility in manufacturing", "mobility in production"
Search period	2000-2022
Screening procedure	The relevance with the research topic is judged by the content of the title and the abstract of every paper

ter stage 2, the literature was categorized for further analysis and write-up in stages 3 and 4. In stage 3, the produced knowledge was analyzed and discussed with academic and industrial experts to decide the suitable presentation format, segmentation of the review, chart types, and analytic tools for the literature review, and the results were compiled, accordingly. Finally, in stage 4, the write-up of the review manuscript was accomplished. The results of the literature review are presented through five major sections in the paper. Sections 1 and 2 present the introduction and description of the methodology. Section 3 is dedicated to the definition of the related concepts and benefits of movable factories. The results related to the use case and requirements analysis are placed in Section 4 while Section 5 is dedicated to discussing the challenges, gaps, and opportunities with modern manufacturing technologies. The results of the literature analysis are summarized in Figs. 3 to 5. In Fig. 3, the number and type of the reviewed documents published between 2000 and 2022 are shown in a histogram plot. The publications are categorized into five major types including journal articles, conference papers, dissertations, book chapters, and technical reports, which are distinguished with a different color in Fig. 3. Most of the publications are among journal and conference articles. The large number of publications in the last few years shows that the movable factory has been an active and timely research area, which also justifies the pertinence of this review.

The literature data is analyzed and the results are visualized using the

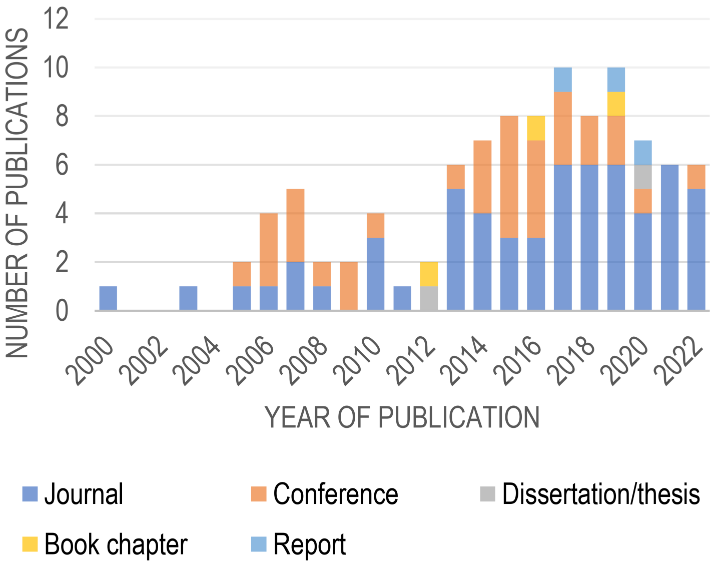


Fig. 3. Number and type of documents per year related to the analyzed literature database.

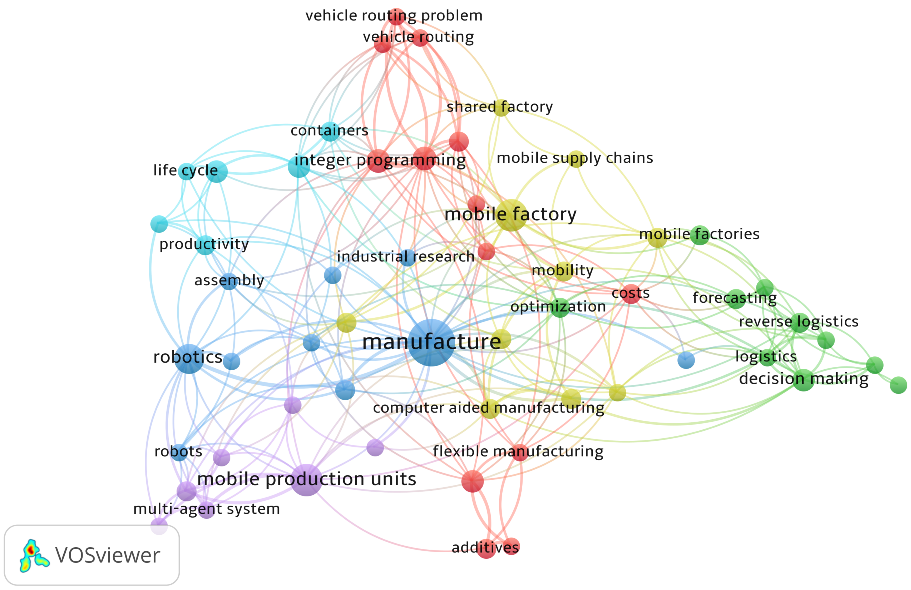


Fig. 4. Network visualization of the keywords in the literature database plotted by VOSviewer.

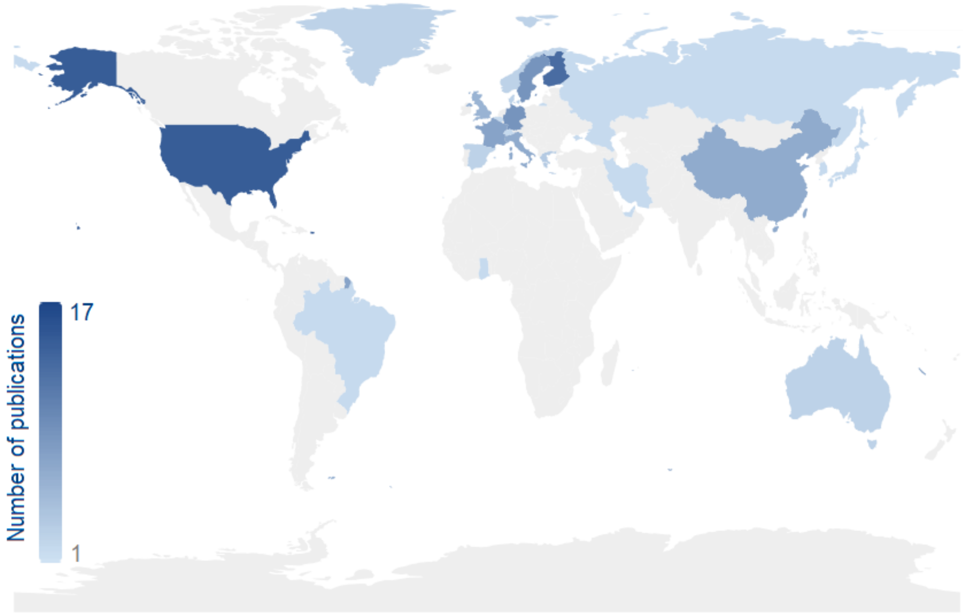


Fig. 5. Geographical heat map showing countries of the first authors of the publications in the literature review database.

VOSviewer software [27]. Fig. 4 shows the keyword map of all subject areas related to the literature database. The analysis is fulfilled considering all keywords including the authors' keywords and the index keywords. The relative size of the nodes shows the usage frequency of the corresponding keyword or research topic whereas the thickness of the links shows the strength of the pairs of keywords. From the figure, the most popular subject areas or keywords among researchers can be easily identified. Likewise, the nodes and keywords with poor connectivity and link to other keywords have the potential to develop into fresh research areas. The VOSviewer clustering analysis tool is used to further organize the key research topics. Accordingly, six major clusters are identified and listed in Table 2. The table shows lists of correlated keywords that have been used together in different references considered for the review. The clusters are also distinguished in Fig. 4 with different colors.

Fig. 5 shows the geographical distribution of the countries associated with the first authors of the reviewed documents. Overall, authors from 22 countries have contributed to the field while authors from USA and Finland have

Table 2
Major topic clusters for movable factories.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
3d printing	Decision making	Assembly	Computer aided manufacturing	Information management	Automation
Additive manufacturing	Economic and social effects	Manufacturing process	Computer software	Mobile production units	Containers
Costs	Forecasting	mobile manufacturing	Mobile supply chain	Mobile robots	Life cycle
Factory automation	Logistics	Portable factories	Mobility	Multi agent systems	Location
Flexible manufacturing	Sustainable development	Project management	Reconfigurable manufacturing	Production engineering	Modular construction
Integer programming	Mobile factories	Robotics	Shared factory	Robot programming	Productivity
Supply chain	Optimization		Supply chain management		
Vehicle routing problem	Recycling				
	Reverse logistics				

had the greatest contributions with 17 and 15 publications, respectively.

3. Mobile Manufacturing

Based on the review methodology described in Section 2, different aspects of the MMSs including the definition and characteristics, life cycle, evolution trend, relevant manufacturing concepts, and main benefits are reviewed in detail and the results are presented through the following subsections.

3.1. Definition and life cycle

The key characteristic of an MMS is that it has *external mobility*, that is, the manufacturing system is able “to change between geographically different places with little penalty in time, effort, cost, and performance” [28, 29]. In [30, 31], the concept of FiaB was proposed and defined as on-demand production capacity featuring flexibility, speed, and mobility. The latter implies that the factory has to be designed as a “mobile platform” which can be easily moved anywhere within the production system, to a supplier or another production site. Based on a theoretical overview of mobility in manufacturing, Stillström and Jackson [28] conclude that there is no explicit definition of mobile manufacturing and that mobility is used as a characteristic in both the operational and strategic domains. Operational mobility may, for example, refer to internal mobility, which is described by Upton [32] as the ability to change quickly between products, or by Wiendahl [33] as the ability to move around manufacturing equipment, e. g., by placing machines on rollers. Strategic mobility refers to a company's ability to efficiently produce its products or services at various locations across different geographical places [28, 34]. This could be enabled by a geographically disperse manufacturing network that can transfer products, processes, and personnel between factories, and potentially move the factories. A generally accepted guideline to achieve external mobility is that the MMS should be able to fit in standard containers [35], either the full manufacturing setup or the dismantled parts [36, 37], such that the whole system can be transported using standard transportation vessels such as trucks, rail, vehicles, and ships [38].

Peltokoski [39] defined the LIM concept and classified the movable factory into three different groups including individual, multiple, and modular movable factories. The individual movable factory consists of one single production unit that is transportable with a shipping container. The multiple and modular movable factories are alike, both consisting of several production units but with different sizes.

In [40, 19], a movable factory was defined as a production unit that can be installed near the customer's location to enable real-time services. A similar definition has also been proposed in [41], in which it is argued that movable factories improve manufacturing flexibility, responsiveness of the supply chain, as well as the manufacturing sustainability. Likewise, Benama [42] proposed a holistic definition wherein the "mobility" is considered concerning the components of the manufacturing system including the technical, human, and information components.

The mobile modular factory otherwise known as "E-plant in a box" was defined in [43, 44] as a low-capitalization installation that can be easily and cost-effectively reconfigured in new locations. Accordingly, mobility is defined as the capability of building, running, packaging, and moving such a factory.

It should also be noted that the MMS has a different life cycle than a fixed factory. The life cycle of the movable factory is illustrated in Fig. 6 (derived based on [29, 45, 42]). Each life cycle phase and its corresponding activities are shown with a distinct color in the figure. Some activities such as warehousing might only be needed under certain conditions and for specific manufacturing cases and thus, they might not be present/mandatory in all MMS life cycles. These activities are distinguished with dashed lines. The life cycle activities shown with solid lines are general and should be sequentially performed in all manufacturing cases.

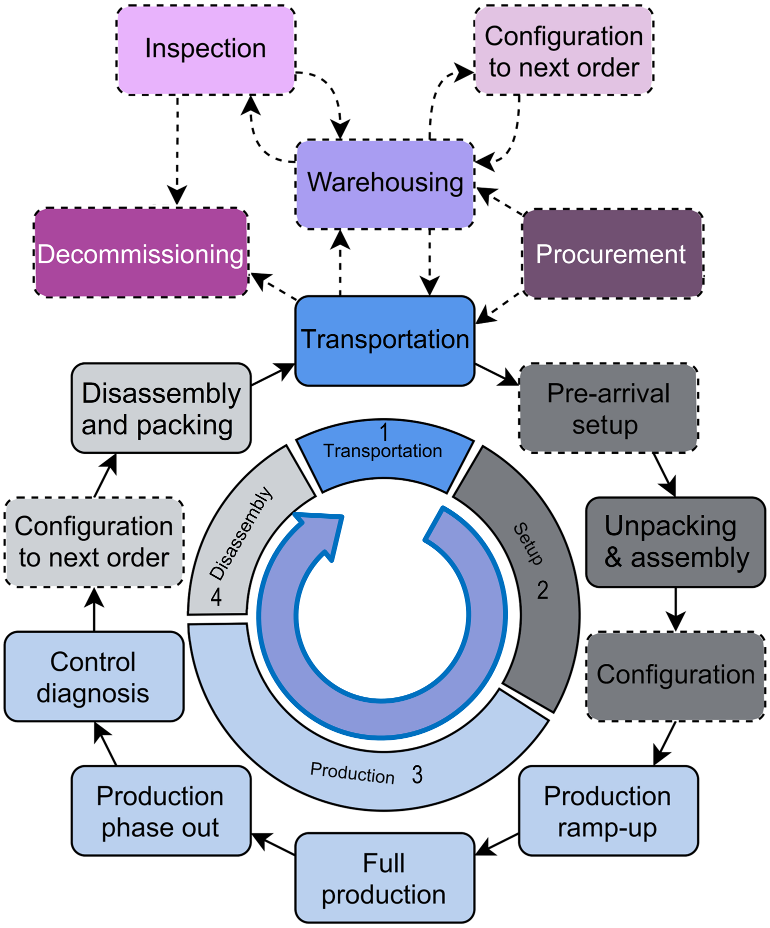


Fig. 6. Life cycle of a movable factory with four main phases including transportation, setup, production, and disassembly. Each phase and its corresponding activities are shown with distinct colors. Solid lines refer to the main life cycle activities whereas dashed lines show occasional activities.

As shown in Fig. 6, the life cycle can be divided into four main phases: (1) Transportation, (2) Setup, (3) Production, and (4) Disassembly. The circular arrow in the middle shows the sequence of the life cycle phases. Each phase might include one or more activities as shown in Fig. 6. For example, the setup phase might include a pre-arrival setup at the customer site, e.g. if the ground needs to be flatted. Likewise, the equipment must be unpacked, assembled/installed, or may also need to be configured before production can begin. The production phase includes production ramp-up, full production,

production phase-out, and control diagnosis. A fast production ramp-up is necessary to be competitive with the fixed factories. Afterward, the MMS should be diagnosed to make sure that the performance is acceptable. After finishing the production, the MMS must be disassembled and packed for transportation to the warehouse or directly transported to the next customer. The latter aspects are covered in the disassembly and transportation phases of the MMS life cycle as shown in Fig. 6.

Apart from these main life cycle phases, there are other activities that might exist in the life cycle of some manufacturing cases as discriminated in Fig. 6 using the dashed lines. For instance, instead of direct transportation from one site to the next one, an occasional off-site warehousing phase might be required. This might occur when, for example, inspection and maintenance services should be fulfilled on the MMS, the MMS needs off-site configuration for the next order, or in case the next order is not placed. The procurement activity occurs when a new manufacturing equipment/service/asset needs to be incorporated into the MMS production cycle whereas decommissioning activity refers to the case when some manufacturing modules/equipment/assets are considered out-of-service, for example, due to breakdowns or degradation of the components.

As seen in Fig. 6, the configuration activity can happen at different phases of the life cycle, either off-site, on-site during setup or on-site during disassembly. The off-site configuration allows the MMS owner to configure and test the MMS before transporting it to the site; however, this will reduce the operational time as the MMS is not transported directly between customers. The on-site configuration during setup allows each order to be handled individually but will require additional time to begin production and parts might be missing for that specific configuration unless a strict configuration control is maintained. The on-site configuration during disassembly has the advantages of an off-site configuration but will require additional time from the customers after production is completed, which might not be possible in all cases. Assuming that the MMS has been configured off-site, it needs to be packed and transported to the customer. The MMS needs to be configured for each order, as there will rarely be two orders that are exactly the same due to the customer need, country/location regulations/requirements/limitations, etc. [29].

Therefore, while a fixed factory has a linear life cycle, i. e., construction then production, and finally decommissioning, in the case of the MMS, the factory will be set up and disassembled multiple times during its life cycle. It should also be noted that the MMS is not able to reach the same throughput as the fixed factories. This is mainly due to two factors: (1) The MMS will not be able to reach the same size, which will prevent the same economy of scale. (2) The MMS will have a lower operational time due to the additional time required for setting up and disassembling. Furthermore, the MMS will probably have a higher frequency of production ramp-up and phase-out than fixed factories.

3.2. Historic overview

The idea of mobile capacity is not a new concept [46]; the military has camps that can be erected in hours; mobile hospitals are used by humanitarian organizations in emergencies; and patents on portable paving plants can be found from 1891 [47]. Nevertheless, the first scientific reference, that we have found, that has mentioned the use of a Mobile Manufacturing Technologies laboratory is from 1993 [48]. However, that facility was exclusively used for educational purposes, not manufacturing, therefore it is not considered in line with other MMSs. Thereafter, the first occurrence we could find of mobile facilities for manufacturing is from 2000 [49]. In addition, it was argued by authors in [46] that before FiaB from 2005, there were "no examples found of adding the mobility factor to a manufacturing system within the engineering industry".

The historical overview and benchmarks in the research of the MMSs and some important industry technological milestones/advancements are shown in Fig. 7. The FiaB conceptualization, characteristics, and requirements definition were first introduced within 2005-2009 in [30, 31, 28, 46, 38, 50]. Soon after, the possibilities and applications of the FiaB concept for Small and Medium-sized Enterprises (SMEs) were explored in [51] wherein FiaB was proposed to realize a product service system for a case company in the metal manufacturing industry. Since then, the FiaB has gained increasing attention among researchers, industries, and SMEs resulting in the maturity of the concept and this further led to the development of new FiaB use cases and business models within 2014-2015 [40, 52, 53]. In the following years until 2017, a similar but broader term, i.e. LIM, was proposed by Peltokoski [18] and solutions were suggested to address the globalization challenges of the movable factories. Under the LIM concept, additional benefits such as using local labor, local material, and semi-ready products were discussed. Most recently, the research on movable factories has been focused on developing mathematical frameworks and models for the movable factory to

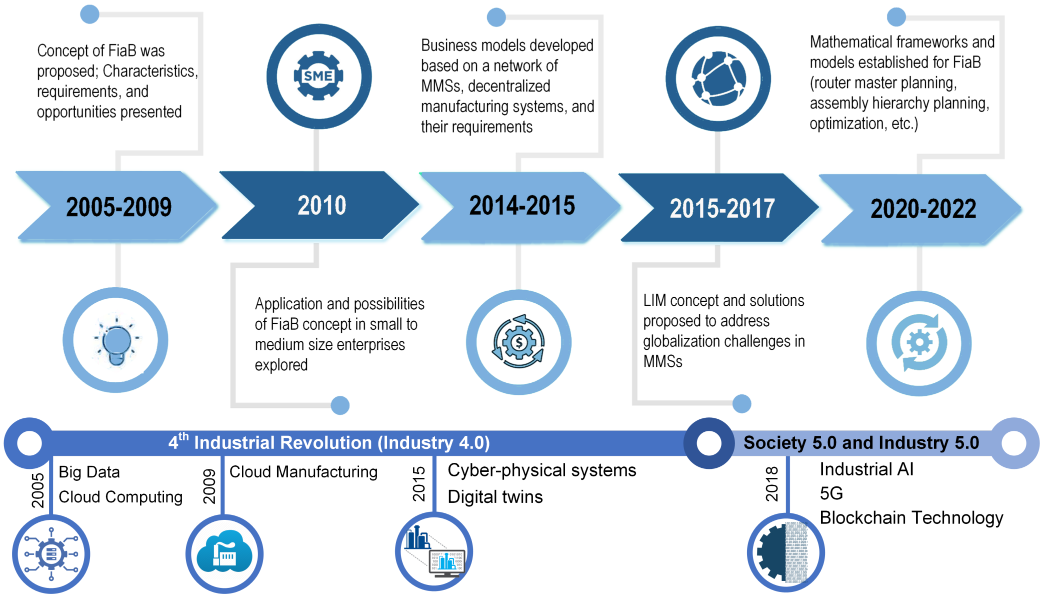


Fig. 7. Chronological history of research on MMSs, industrial revolutions, and emerging industrial technologies.

achieve optimal planning and decision making, for example, router master planning [54, 55, 56, 57, 58], assembly hierarchy planning [59], facility location optimization [60], and decentralized decision-making for FiaBs [61].

In Fig. 7, the time relevance of the MMS research with the evolution of industrial revolutions and technologies is also depicted. Industry 4.0 refers to the fourth industrial revolution which involves the integration of digital technologies such as Internet-of-Things (IoT), big data analytics, and Artificial Intelligence (AI) to increase autonomy, efficiency, productivity, and flexibility in manufacturing processes. More recently, Industry 5.0 is put forward, which emphasizes the integration of human intelligence and collaboration with technology to create a more human-centered approach to manufacturing. Industry 5.0 seeks to build on the strengths of Industry 4.0 but also recognizes the importance of human skills and creativity in the manufacturing process [62, 27]. Society 5.0, on the other hand, is a concept that describes a vision of the future society that is both technologically advanced and human-centric and as described in [63] includes three main pillars: (1) human centricity, (2) resilience, and (3) sustainability. The movable factory concept is well-suited to both Industry 4.0 and Industry 5.0 as it enables a flexible and adaptive manufacturing approach that leverages advanced technologies such as digital twins (DTs), AI, etc., and supports human-machine collaboration. The characteristics of movable factories such as the emphasis on the local workforce and production sustainability are also aligned with the requirements of Industrial 5.0 and Society 5.0. Application of new industrial technologies in the context of the movable factory is discussed in more detail in Section 5.

3.3. Related concepts

This section reviews the emerging manufacturing concepts and their link with MMSs. The review is detailed in Table 3 and contains nine emerging manufacturing paradigms including Reconfigurable Manufacturing System (RMS) [64, 65], Modular Production System (MPS) [66], Dedicated Manufacturing System (DMS) [67], Flexible Manufacturing System (FMS) [68, 69], Distributed Production System (DPS) [70, 71], micro-factory [72, 73], flying factory [74, 75], FiaB [38], and MMS [45]. Different criteria related to the movable factories are also listed in Table 3 and the manufacturing concepts are evaluated against them. The characteristics of the MMS and FiaB are very close to each other except that for the latter case internal mobility has not been reported as a main feature. Therefore, the two concepts have been interchangeably used in the literature. According to the review, one of the main limitations of the existing manufacturing concepts compared to the MMS is the lacking emphasis on mobility. Likewise, except for the MMSs and MPSs, none of the manufacturing concepts emphasizes modular production to facilitate mobility. Therefore, for manufacturing cases in which it is preferred to have mobile production, the MMS concept offers a significant advantage.

Another relevant manufacturing concept that emphasizes the decentralization of production is referred to as global production network (GPN) [76, 77]. The GPNs are typically characterized by the fragmentation of production processes, with different stages of production taking place in different parts of the world, and the close coordination of activities among the various actors involved [78]. The movable factory concept can facilitate the GPNs by enabling companies to establish a presence in different regions of the world without committing to long-term investments in fixed infrastructure. This flexibility allows companies to benefit from comparative advantages of different regions, such as access to (cheaper) natural resources, skilled labor, or

Table 3
Review of emerging manufacturing concepts and the related focus areas.

No.	Ref.	Concept	Definitions and objectives	Focus criteria								
				Internal Mobility	External Mobility	Speed	Modularity	Changeability	Near the end user	Local resources*	Volume Changes**	Needs Change***
1	[64, 65, 17, 35]	RMS	Formed of standardized assets enabling rapid change in production volume or type; Reconfigurability may refer to machines in a system or modules/mechanisms in machines			✓		✓			✓	✓
2	[66]	MPS	Formed of standardized factory-preassembled blocks/modules, which can be easily interconnected to build a product; MPS features simplified maintenance, lower downtime, scalable capacity, and lower costs	✓		✓	✓				✓	✓
3	[67]	DMS	Designed to manufacture a single part at a high production rate through fixed simultaneous operations			✓					✓	
4	[68, 69]	FMS	Designed to have built-in flexibility to manufacture multiple products at low production volumes; Flexibility is often defined as production system ability to alter its behavior without the need for reconfiguration					✓				✓
5	[70, 71]	DPS	Formed of smaller decentralized and geographically dispersed manufacturing facilities much closer to the end user						✓	✓		✓
6	[72, 73]	Micro Factory	Designed to minimize the production system size to match with the size of the parts; also known as desktop factory; Savings in space, energy, and costs achievable						✓	✓		
7	[74, 75]	Flying Factory	Manufacturing in temporary off- or near-site locations based on technologies and processes that are easy and quick to setup and dismantle; Also known as temporary manufacturing factory			✓			✓	✓		
8	[38]	FiaB	Consists of standardized manufacturing units, which can be installed in a container and are easy to be transported to external sites		✓	✓	✓	✓	✓	✓	✓	✓
9	[45]	MMS	Formed of manufacturing modules that are placed on a movable platform; Mobility refers to both internal and external mobility	✓	✓	✓	✓	✓	✓	✓	✓	✓

* Including labor and/or raw material. ** Ability to handle changes in production volume. *** Ability to adapt to changing customer requirements.

favorable regulatory environments. Both concepts involve the use of flexible and adaptable production strategies that allow companies to respond quickly to changing market conditions and to take advantage of the opportunities presented by different regions of the world [79].

3.4. Main benefits

The benefits of the MMSs are illustrated in Fig. 1. One of the main benefits is that the factory can be moved to the location where it is most useful, which reduces the need for transportation and its associated costs. One option is to move the MMS close to the customer or consumption site and this will allow components to be transported more compactly than the final product. An example in the wind industry is the transportation of the metal sheets rather than wind turbine tower sections. At the same time, the close vicinity to the customers allows a shorter reaction time to the changes in the customers' requirements because of the reduced transportation time between the factory and the customer. This also creates the possibility of using local labor for manufacturing. This aspect and the lower transportation emissions will improve the social and environmental sustainability of manufacturing [80, 81]. The MMS could also be moved close to the materials that it should process, which enables the producers of the materials to process the materials further and get a better price for their product [82, 22], e. g., in food production, the MMS can allow the farmers to refine their products [83]. In addition, movable factories facilitate the Just-in-Time (JiT) delivery to minimize the required storage space for material, and this makes the system robust to the market/logistics uncertainties [14]. Another option is to move the MMS between fixed factory locations as a means to have shared equipment between sites. This enables several advantageous use cases. For example, sharing expensive assets, managing occasional production peaks, or using movable units as a temporary backup resource to handle machine shut-downs or to enhance production capacity when necessary [56]. It could also be the case that such assets will be used in the same company when that asset is needed, occasionally. Likewise, this can enable manufacturing affinity [84] and new business opportunities, such as leasing equipment, service as a product, and joint ventures [12].

Another important benefit of the MMS is the possibility of having a high Capital Expenditures (CapEx) return. CapEx is the funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment [85]. For MMSs, most of the CapEx investment put into the buildings and equipment can be returned to the company after the order has been completed and reused at the next site. This reduces the risk related to the CapEx as it is easier to use the factory for multiple orders. For the fixed factory, the return on investment is bound to an estimated prognosis of the orders that should be completed. On the contrary, the MMS can allow a more uncertain prognosis for local demand.

The CapEx return allows for new market opportunities by mitigating the barriers against starting production in a different country. This is emphasized in countries with local content requirements, i. e., when a percentage of the production must take place in the country where the product is sold. For a fixed factory, the risk related to entering this market is high as there is no guarantee that further orders will follow. For MMSs, this is less of an issue as the factory can be moved to another location after the completion of the order with local requirements.

Table 4 summarizes the benefits of the MMSs compared to fixed factories. It should be noted that the suitable choice between a movable factory and fixed factory depends on the specific manufacturing requirements, which may vary from one application to another. In some manufacturing cases, movable factories can be more expensive to operate than fixed factories due to additional costs of transportation, setting up, and dismantling. However, movable factories can be more cost-effective in certain situations where the

Table 4
Summary of the comparison between MMSs and fixed factories.

Criterion	MMS	Fixed factory
Mobility	Easily movable making them more versatile and adaptable to changes in demand or supply chain	Difficult or impossible to move to a new manufacturing location
Size and capacity	Generally are small in size and have relatively low production capacity due to the limits on the size and complexity of the modular equipment/infrastructure	Generally can be large and can achieve a large production capacity
Transportation of finished products	Minimal transportation need since the manufacturing is close to the customer's place	Transportation of heavy products can be expensive or in some cases impossible
Distance to customer	Manufacturing can take place close to the customer's vicinity	Production is done in a fixed location
Local resources	Possibility to use local material and/or workforce at the customer place	Difficult to use local resources
Environmental sustainability	High sustainability by reducing transportation needs/emissions	Larger environmental impact as they are built on a permanent site and may require significant infrastructure and resources
JiT delivery	Facilitated JiT reduces the storage space and warehousing	More vulnerable to market/logistics uncertainties
Shared equipment	Possible to share expensive equipment/assets to cover production peaks	Difficult to share equipment. New investment might be needed to cover production peaks

benefits of mobility outweigh the extra costs.

4. Literature Review

In this section, the literature taxonomy and classification, MMSs' requirements, application domains, and use cases of the MMSs are reviewed and presented through the below subsections.

4.1. Literature taxonomy and classification

The literature taxonomy and classifications criteria for the analyzed literature database are shown in Fig. 8 [86]. The classification is fulfilled based on several MMSs characteristics such as their size, mobility, distance to headquarters, etc. The classification criteria are explained in the following.

- Changeable Manufacturing System: Flexible and/or reconfigurable manufacturing system
- Size: Single container, multiple containers, dismantled factory
- Mobility: External (near site, on-site, or at materials/product), internal
- Material setup: Component, kit-assembly, final assembly, or testing
- Distance to headquarters: Organizational, time, geographical, technological, social and cultural
- Workforce: Pre-/post-operating labor (local or fixed), operational labor (local or fixed)
- Knowledge transfer: Physical or digital (manual or automatic)
- Time at site: Setup time, and operational time

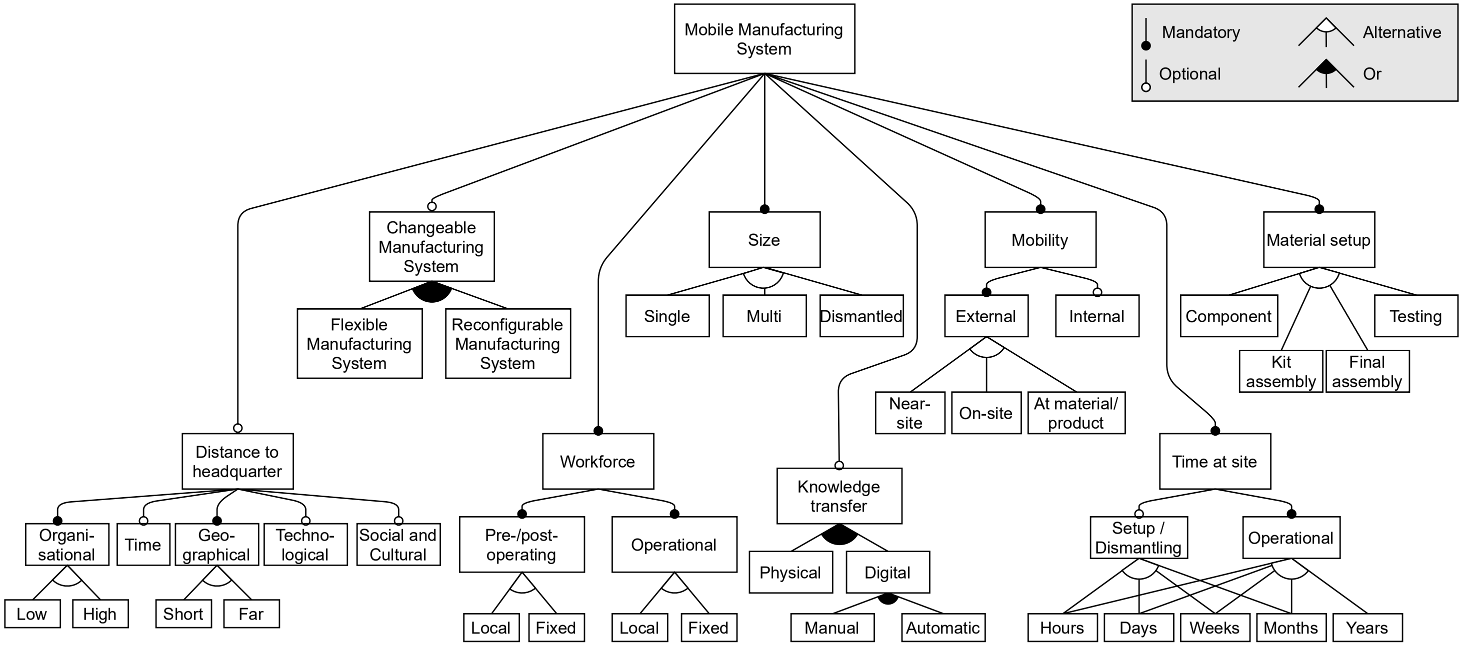


Fig. 8. Feature model for MMS.

4.2. Applications and use cases

The use cases of the MMSs are diverse and cover a range of application domains in different industrial sectors. This includes, for example, the production of biofuels using movable factories [87], mobile recycling units for recycling of construction [88] and electronic equipment material [89], additive manufacturing based on portable 3D printing units [90], etc. The use cases and applications are comprehensively reviewed in Table 5. Based on the literature analysis, Fig. 9 shows the percentage of the MMSs' use cases for 16 different industries. The figure shows that MMSs have been mostly studied within the context of construction (19%), biomass (15%), and food industries (13%), as well as additive manufacturing (8%).

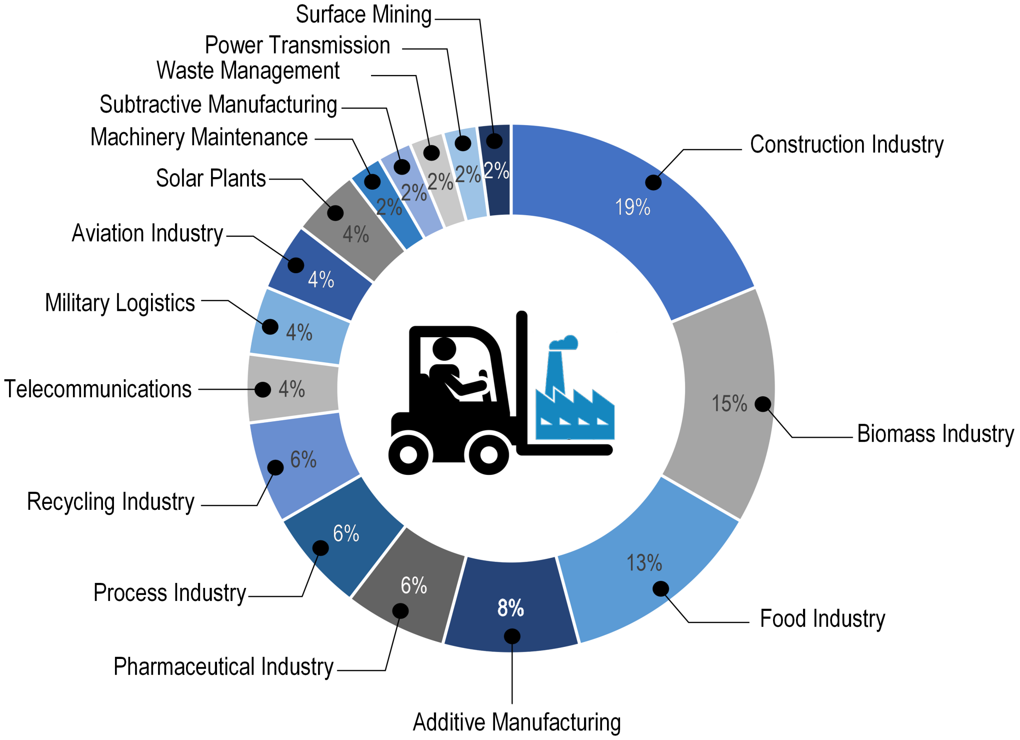


Fig. 9. Different industry sectors using the MMS concept.

4.3. Requirements

According to the literature, the three main requirements of movable factories are mobility, speed, and flexibility. As discussed, mobility can be of two

Table 5
Applications and use cases of MMSs reported in the literature.

Application area	**Ref.**	**Use cases**
Food industry	[91, 83, 92, 93, 94]	A concept known as “travel factory” in a portable shipping container designed by Unilever; End-to-end production process from material to packaging; All-in-one utility capabilities [91];MMS application for production of cocoa paste close to cocoa bean farmers to enhance sustainability [83]; Application of mobile poultry processing units offering lower start-up cost, increased product quality, possibility of equipment leasing, etc. [92, 93].
Pharmaceutical industry	[95, 57, 96]	Portable continuous miniature and modular system offered by Pfizer [95]; Vaccination projects wherein the final products (i.e., vaccines) were assembled at the customer locations, as inspired by FiaB concept [57, 96].
Telecommunications	[97, 19]	FiaB concept developed by Nokia consisting of Lego-like containers that can be packed, shipped, and brought to operation within a few hours; Movable communication facilities for providing service to a region with temporal and spatially distributed demand.
Additive manufacturing	[98, 90, 99, 100]	3D printing units that can be packed, transported, and re-installed very quick.
Machinery maintenance	[101]	Concept used for maintenance of agricultural machinery to enable fast and reliable maintenance services for failed machines.
Subtractive manufacturing	[102]	MMS used for drilling and milling operations of small features such as notches, holes, etc. to better handle the customer demand variations in mass produced parts.
Waste management	[103]	Miniaturized mobile recycling unit embedded into containers
Military logistics	[104, 105]	Mobile military medical evacuation units and military logistics
Aviation industry	[106, 107]	Used in assembly of airplane wings by substituting large fixtures used in assembly lines of large structures with small mobile robots [106]; MMS used in production of spacecrafts and spaceships fuel from the ore found on the lunar surface; MMS used to move between locations that fossil deposits are located [107]
Process industry	[61, 56, 55]	Optimized mobile factory routing problem and production scheduling at the customers locations
Construction industry	[108, 109, 14, 110, 75, 37]	Schedule the movement of mobile concrete batching facilities in railway construction projects
Biomass industry	[111, 112, 113, 114, 115, 116, 117]	Production of bio-fuel based on MMSs [111, 116, 113]; Bio-oil production based on mobile refineries [112, 115]; Using several semi-mobile processing units to supply a large coal-fired plant [114]; Using mobile grinder system [117].
Recycling	[88, 89, 118]	Using mobile recycling centers for on-site recycling of construction material [88]; Movable plants for recovery of valuable metals from waste electrical and electronic equipment [89, 118]
Solar plant	[13]	Movable factories used for producing and installing solar farms to reduce transportation costs, cover larger area, and reused at least 5 more farms
Power transmission	[36]	Mobile factory used for assembly and welding process in transmission lines to reduce the need for transport and product cost
Surface mining	[119]	MMS used in surface mining to produce and deliver explosive compound in mining operations

different types: internal and external mobility. External mobility is deemed as the key prerequisite when the factory needs to be geographically moved. In addition to mobility, a movable factory should fulfill the movement process with little penalty in time and effort. Therefore, a movable factory has also sufficiently fast transitions between different life cycle phases. In each life cycle phase, different settings need to be adjusted which demand flexibility in equipment, operations, processes, material handling, routing, etc.

The overview of different requirements for movable factories is provided in Fig. 10. In this figure, the three main characteristics, i.e. mobility, speed, and flexibility appear in the center layer, and in the middle layer, the potential

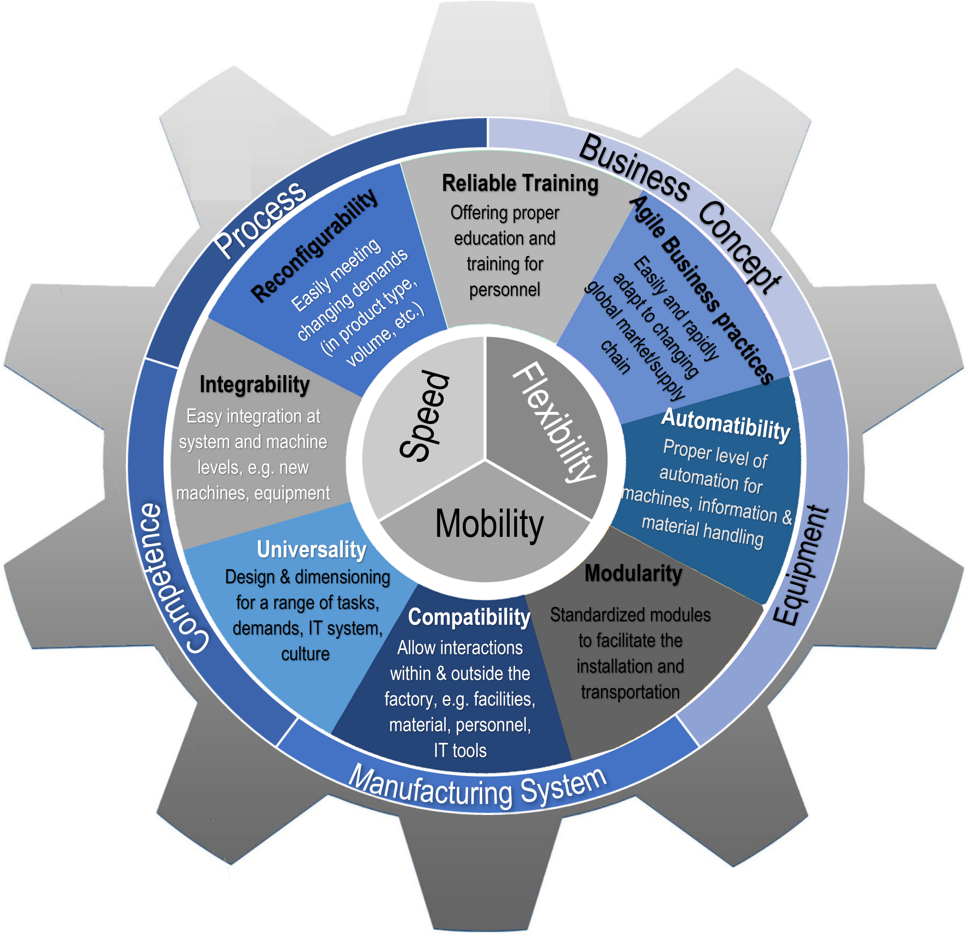


Fig. 10. Overview of movable factories requirements.

factors that satisfy/facilitate these three main requirements are shown. The requirements are broad but not all of them are necessarily for all use cases. The requirements are related to five manufacturing aspects including manufacturing system, equipment, processes, competencies, and business concept, as depicted in the outer layer of Fig. 10.

The requirement related to the modularization refers to the implementation of small and transportable modules which can be easily assembled and disassembled to facilitate mobility, improve flexibility, and improve speed in relocation, reconfiguration, volume capacity change, etc. [41]. Reconfigurability improves the responsiveness to manufacturing changes and supports the flexibility requirement [120]. Reconfigurability has been defined as the ability to add, remove, or rearrange the structure and configurations/settings of the manufacturing system in the desired manner [41]. The responsiveness to changes can also be facilitated/accelerated by increasing the automation level. An appropriately automated system can overcome labor shortages and reduce errors caused by human involvement.

Another enabler of the movable factory is integrability. The integrability can be met by designing standardized interfaces that enable the integration of machines, information, control, etc. at the system level and easy and fast integration of part modules at the machine level [50]. Likewise, the universality requirement ensures that the movable factory should be properly dimensioned and structured to handle diverse tasks, demands, functionalities, cultures, economies, IT infrastructures, etc. [33]. To tackle diversities and interactions inside and outside of the manufacturing system, creating compatible physical and logical systems/solutions is needed. The compatibility requirement ensures manufacturing compliance with different types of potential materials, information, etc. Through utilizing uniform interfaces, it also enables the incorporation/disconnection of the products, components, processes, or production facilities in the existing manufacturing structures and processes with a limited effort. Finally, the movable factory should meet requirements related to reliable training and adopt agile business practices [12] to address the challenges related to the local resources (unskilled local workforce), continuously changing supply chains, and market requirements.

5. Discussion on Challenges, Research Gaps, and Opportunities

In this section, the challenges of the MMSs are reviewed and research gaps are discussed. Likewise, the opportunities related to the MMSs including the possibility of applying cutting-edge technologies such as IoT, augmented reality (AR)/virtual reality (VR), DT, etc. to address the existing MMSs challenges are presented. Based on the challenges and opportunities, potential future research domains are identified and presented in this section, as well.

5.1. Challenges in the implementation of the MMSs

Many challenges have been identified regarding the implementation of the MMSs. As shown in Fig. 11, the challenges can be classified into six major groups including issues related to the equipment, logistics, regulations, etc. Some of the topics are similar to those for fixed factories. However, some might be more profound for MMSs than fixed factories, such as finding labor and training, which are challenges that must be handled in any case, but for MMSs this must be tackled more often and possibly without the factory available at the time of hiring and training (unless the factory has moved to manpower place). Other challenges such as setup and dismantling are specific to the MMS. In the following subsections, the challenges are discussed in more detail.

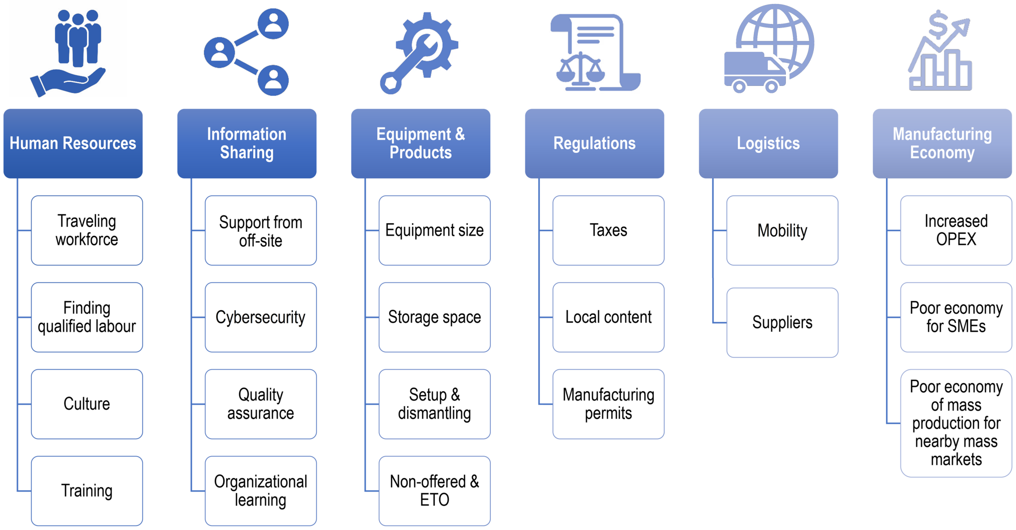


Fig. 11. Classification of different challenges for implementation of the MMSs.

5.1.1. Human resources

- Traveling workforce: When using a traveling workforce, there will be traveling expenses that must be covered, and the hourly cost of such a force will probably also be more expensive than the temporary local workforce. Furthermore, if the MMS is moving between countries, it may not be allowed to use a large workforce from another country [121].
- Find qualified labor: If the manufacturing processes are complex, it might be hard to find qualified labor, especially in the case of entering a new market where the company has not established a reputation [122].
- Culture: Different countries have different work cultures, which will need to be adequately handled at each location [16].
- Training: Training of a new workforce is time-consuming and expensive. Furthermore, if the training requires the use of manufacturing equipment, the training cannot start before the MMS has been set up and it will prolong the time before the capacity of the factory can be reached [123].

5.1.2. Information sharing

- Support from off-site: It is usually expensive to have “master operators” travel to the locations of the MMS [124].
- Cybersecurity: Movable factories may require remote access to shared information and data. Infrastructure that will be used to serve this purpose is often vulnerable to cyber attacks [125]. Preserving the privacy and security of data and IT systems can be challenging [126].
- Quality assurance: Environment changes still need to provide proof of quality [71].
- Organizational learning: Passing the learning from each MMS to the organization can be difficult and time-consuming [70].

5.1.3. Equipment and products

- Equipment size: It is recognized that the manufacturing equipment must be easy to transport and they should be able to fit in standard containers. Otherwise, special transportation practices will be required, which reduces the mobility [18, 127].

- Storage space: The storage space needed for the MMS will potentially vary between locations. This has to be carefully considered before starting operation since a small storage space will put tight constraints on the delivery of materials/parts and a large storage space comes with extra expense [128].
- Setup and dismantling: The time it takes to set up and dismantle the MMS results in reduced operation time, which means the profit will decrease. Hence, it is important that the time it takes for setup/dismantling is small relative to the operation time. Reducing the setup/dismantling time will enhance the MMS availability to be used in additional cases [18].
- Non-offered and Engineer-To-Order (ETO): Manufacturing lines are often designed according to the current products with poor changeability to accommodate with the requirements of non-offered products and ETO products [129].

5.1.4. Regulations

- Taxes: The tax systems in different countries are different and more complicated when setting up a temporary factory as opposed to building a fixed factory [18].
- Local content: The legislation between projects and countries could be different. It might also not be possible to use non-local workforce [129].
- Manufacturing permits: Acquiring manufacturing permits could be challenging for the MMSs. Most of these are made for fixed factories, which might prove troublesome for temporary setups. There might also be political barriers related to the sustainability aspect of the MMSs [25].

5.1.5. Logistics

- Mobility: Movement between sites and delivery of materials/parts to the MMS is challenging [40].
- Suppliers: Changing suppliers at each site is difficult. For MMS, there is also a much higher dependency on what happens at each customer, as delays at one customer will prevent the MMS from moving to the next customer. Thus, the challenge lies in accurate time estimations

for each operation [56]. Also, closer collaborations between multiple departments in the company are needed [16].

5.1.6. Manufacturing economy

- Increased OPEX: Even though there will be a high CapEx return, the operational expenditures (OPEX) will probably increase when using an MMS since there will be time "wasted" on setup and tear-down, plus the use of new workforce every time will require ramp-up at every location, which increases the operational time and results in increased OPEX [23].
- Poor economy for SMEs: The concept of the MMS is not economically attractive for SMEs [130].
- Poor economy of mass production for nearby mass markets: The economy of MMSs could be challenging for heavy industrial processes (for example, converting iron to steel needs a large amount of energy and space [23], or in the case of mass production for nearby mass markets).

5.2. Research gaps and opportunities

Although the MMS concept has attracted considerable interest from different stakeholders in academia and industry, several gaps in the knowledge domain and implementation challenges need to be addressed yet. Emerging tools and technologies such as IoT, DTs, modeling and simulation (M&S) [132], additive manufacturing, AR/VR, etc. can help address some of these challenges/gaps to meet the MMSs requirements. Table 6 presents an overview of these modern technologies and their opportunities for the realization of the MMSs. Likewise, the current technology readiness level (TRL) of each technology and its fit to the MMS life cycle are summarized in Table 6. Detailed descriptions are provided in the following:

- IoT: IoT technology can be used to collect and process a large amount of data from a network of physical objects in the manufacturing system. This allows companies to make more informed decisions, optimize operations, and enhance efficiency. The current TRL of IoT technology is reported at level 7 [131]. TRL 7 equivalents system prototype demonstration in an operational environment. Despite the advancements, IoT technology is still expensive, which hinders its applicability, especially for small-size companies [133]. In addition, the cybersecurity of IoT

Table 6
Overview of the emerging manufacturing technologies and their fits in the MMS concept.

Technology	TRL*	Technology gaps	Opportunities for MMS realization	Fit in MMS lifecycle
IoT	7	-Vulnerable to cybersecurity threats -Poor affordability especially for smaller companies -Complex data integration due to different data formats/structures/protocols -Difficult to assure data consistency/accuracy/reliability across multiple data sources	-Remote monitoring/control of operations -Supply chain/stakeholder management to track/manage inventories and suppliers -Real-time data analytics for rapid decision-making, e.g., in case of uncertainties such as weather change	All
DT	6	-Low scalability to outweigh implementation cost -Privacy concerns and lack of proper cyber-attack countermeasures -Poor data interoperability	-Design optimization for factory layout planning, equipment placement, and minimizing need for physical modifications -Faster and efficient quality assurance -Automated reconfigurability	Setup Production Disassembly
VR /AR	6-9	-Poor affordability -Specialized skills/tools required for content creation of complex and interactive environment -Lack of standards, poor software/hardware interoperability	-Effective training of staff regarding the safety and operation of MMS -Simulation of factory processes for design validation -Remote collaboration between workers and experts for design, troubleshooting, and maintenance tasks	Setup Production Disassembly
3D printing	8-9	-Poor scalability for large-scale production -Lack of proper standards for procedures regulation and quality control -Low printing speed for mass production	-Speeding up prototyping and development cycles of MMSs -Reduced inventory and storage space requirements	Setup Production
Block chain	7	-Lack of scalable solutions for large-scale applications -Lack of proper international standards	-Supply chain transparency and accessibility -Smart contracts -Decentralized data management	All
AI	6	-Difficult to access a large amount of rich data for training	-Optimized scheduling, planning, resource allocation, inventory management -Decision support for managers/operators to achieve informed decisions based on real-time data and insights -Faster and efficient quality control	All
M &S	6-9	-Large computations for physics-based models -Poor standardization for modeling tools/methods	-Virtual prototyping -Performance analysis -Training and education	Setup Production Disassembly
Robotics & Automation	7	-Complex task handling for high-level cognitive abilities/adaptability -Poor integrability of robots/automation systems/equipment from different vendors -Challenging workforce adaptation and skillset	-Enhanced internal mobility using mobile robots -Reducing manual labor, improving safety -Rapid reconfiguration or relocation of the factory setup	Setup Production Disassembly

*TRL range is given considering different industrial sectors and application domains.
The TRL is provided based on statistics in ENTSO-E Technopedia [131]

systems becomes very critical and challenging in an industrial setting and this aspect still requires further exploration [126].

As discussed in [65, 134], IoT can be used to establish production processes that are optimized over the entire manufacturing life cycle. When it comes to the MMS, the IoT facilitates information sharing (as outlined in Fig. 11) and can help manufacturers to meet MMS requirements throughout the whole MMS life cycle by quickly adapting to rapid changes, optimizing the production flow, remote monitoring and control of factory operation, and management/optimization of the supply chain.

Emerging technologies such as 5G, big data analytics, and cloud computing [135] are closely linked to IoT and facilitate its application and implementation in movable factories. 5G refers to the fifth generation of wireless communication technology that features faster data transfer speeds, lower latency, higher device density, and improved reliability compared to previous cellular networks. This technology can provide the necessary network infrastructure to handle the massive number of connected devices and enables efficient communication between these devices. Moreover, utilizing big data analytics [136] helps extract insights and value from large and complex datasets gathered from various sources such as sensors, equipment, production lines, and supply chain systems. Big data analytics can be facilitated by cloud computing platforms, as they provide a flexible and scalable platform for managing the computing and storage needs of the movable factories. It enables secure data storage, processing, and remote access, allowing movable factory stakeholders to collaborate, monitor operations, and make informed decisions in real time. With regards to cloud computing, methods such as edge computing and fog computing [135] can be utilized to bring computational resources closer to the data source or end user, facilitating faster data processing, reduced latency, and improved system performance.

- DT: The DT refers to the digital replica of a tool, machine, process, or even a whole manufacturing system [137, 138]. According to the recent report [131], the DT has an existing TRL of 6, which refers to the demonstrated technology in a relevant environment. The technology is still expensive and lacks scalability. Similar to the IoT, DT suffers also from cybersecurity threats [126]. Proper countermeasures have to be devised and put in place to enhance the TRL of the DT. The DT technology can address the MMS challenges in several ways. For example, it could be used to speed up the assets reconfiguration and shop floor re-planning when the factory moves, through virtual testing of several configurations/plans to acquire optimized manufacturing settings. Instead of conventional quality assurance methods which are very time-consuming (also because of the frequency of the moves), one can use DT to automate the quality control tests in a virtual setup, similar to the one reported in [139]. The DT also leverages the design and optimization processes [140] wherein state-of-the-art control and optimization algorithms and machine learning approaches can be applied to circumvent difficult and time-consuming design validation tests [141]. The DT can fit in the setup, production, and disassembly phases of the MMS life cycle.

- AR/VR: AR/VR technologies allow interaction with digital content in engaging and immersive ways. They can be used for off-site assistance, training of the staff, and/or visualization and perception of abstract data, designs, and analysis models. In terms of the TRL scale, VR/AR technologies are given a TRL range from 6 to 9 [131] depending on the specific application or industry sector.

  The advances in M&S tools with 3D modeling and embedded VR capabilities allow more sophisticated analysis and interactions with the models, which provides effective communication and collaboration solutions. This will particularly help to address the MMS's challenges regarding the training of the staff, off-site support, and organizational learning. This, in turn, reduces the need for the traveling workforce [124]. The technologies will thus fit in the three life cycle phases of the MMSs, namely in the setup, production, and disassembly of the MMSs.

  Despite the high TRLs achieved, the technologies yet face challenges regarding the lack of standards, poor interoperability of the related software/hardware, and difficulty to create content for interactive and complex manufacturing environments [124].

- Additive manufacturing (3D printing): As opposed to subtractive manufacturing, in additive manufacturing, materials will be joined to make objects, usually layer upon layer [142]. Additive manufacturing is a mature technology with a reported TRL scale of 8 to 9 depending on the specific industry sector and application area [131]. Despite its maturity, the scalability for industries that require large-scale and mass production is still challenging. In addition, the technology lacks proper standards and regulations to assure the quality of the products printed with additive manufacturing [143].

  The additive manufacturing technology offers reduced development time and cost for rapid prototyping as it can be directly derived from a 3D CAD model [144]. With this technology, it is easier to manufacture products at/close to customers thereby shortening the response time to customer changes as outlined as a key feature for movable factories. The latter point will also help to reduce the inventory and storage space requirements. In terms of the MMS life cycle, additive manufacturing can be most helpful for the setup and production phases.

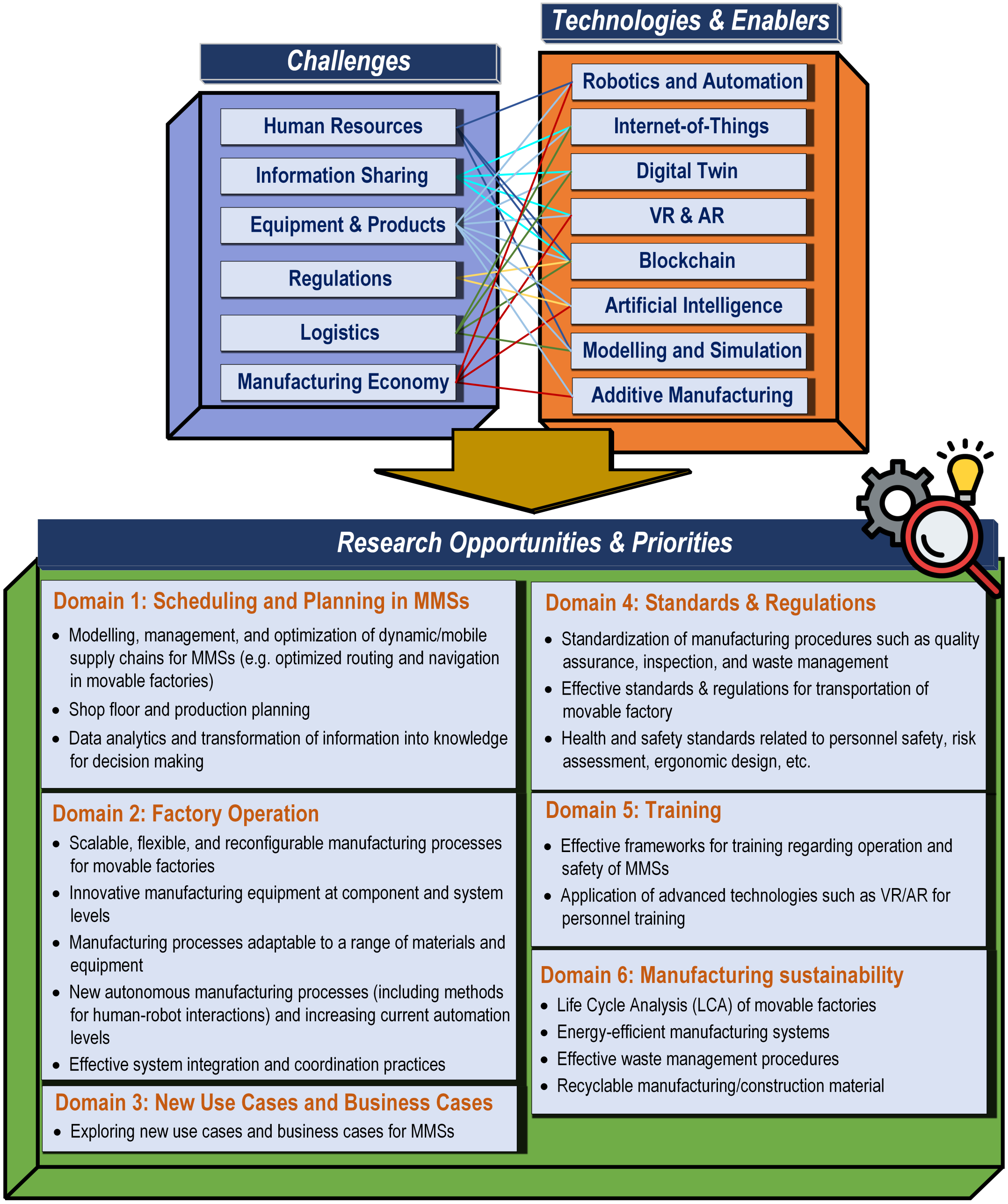
- Distributed Ledger Technology (DLT) and blockchain: DLT is a decentralized and transparent system for recording, verifying, and maintaining transactions or data across multiple participants or nodes in the network. The DLT can be used to enhance privacy and trust in movable factory systems, e.g., to transparently store machinery's usage data as a basis for pay-per-use business models on the manufacturing shop floor [145]. Blockchain is one of the most well-known and widely implemented designs of DLTs [145]. The current TRL scale of blockchain technology is reported at around level 7 [131]. The major technological gap for blockchain is the lack of standards, and regulations as well as scalable solutions for large-scale industrial applications. Ensuring transparency and security of information in a distributed setting across the supply chain of movable factories is challenging. A promising solution could be to apply blockchain technology to create a resilient, transparent, and secure log of manufacturing activities such as transactions and movements of goods and materials within the supply chain of movable factories [146].Using blockchain, it is possible to automate supply chain processes and transaction costs through a concept known as a smart contract [147]. Through decentralized data management, the blockchain can also help to improve the security and integrity of manufacturing data at all life cycle stages of the MMSs.

- AI: AI technology uses algorithms and statistical models to analyze and interpret data, learn from experience, and use it to improve manufacturing performance over time. As of now, AI technology has been generally validated up to a TRL of 6 [131]. Implementation at higher TRLs is challenged by the lack of access to rich manufacturing data, which is required to train AI algorithms. AI can be beneficial in different stages of the MMS life cycle. In the production phase, AI-powered systems can be used for quality assurance processes [148] e.g., by inspection of the products through AI-driven computer vision systems. As for the assembly and disassembly stages, AI systems can be used to optimize the supply chain by scheduling, planning, resource allocation, and management of inventories. AI can also be used as a decision support system for managers and operators to help them achieve more informed decisions based on real-time data and insights.

- M&S: Mathematical and computer-based models can be used to create a virtual model of the factory and its processes. The virtual model can be used to test and validate different layouts, equipment configurations, and workflows to optimize the factory's efficiency and productivity. The TRL for this technology varies from one application to another. The current TRL scale has been reported in the range of 6-9 [131]. Regarding the technology gaps, two main challenges can be highlighted. First, a large computational capacity is needed to run complex models, especially physics-based models [149]. Second, there is a lack of standards for the tools and methods used for modeling and simulation of the factories [149]. Models and simulations can be fulfilled for various purposes such as virtual prototyping, training and education, and performance analysis of a production line [150]. Thus, the technology provides opportunities in all life cycle stages of the movable factory.

- Robotics and automation: Applications of robotics technologies and automation can help movable factories to achieve increased productivity, flexibility, efficiency, and reduced need for the workforce. Automation can be applied to various machinery and equipment used in the movable factory including automated assembly systems, robotic arms, conveyor systems, packaging machines, and inspection systems [151]. For instance, mobile robots and automated guided vehicles can be utilized to transport material and components between different workstations within the factory. Collaborative Robots (Cobots) can be used to perform repetitive or physically demanding tasks to improve ergonomics and enable efficient human-robot collaboration within the factory. Overall, an increased level of automation enables streamlined operations, improves safety, reduces manual labor, enhances productivity, and allows for rapid reconfiguration or relocation of the factory setup [21]. While robotics and automation technologies play a vital role in realizing a mobile and agile manufacturing system, there are still some gaps that need to be addressed. For instance, integrating robots, automation systems, and manufacturing units from different vendors can be quite challenging as there is no standardized protocol and platform for integration [21].

The discussions of subsection 5.1 and the current subsection about challenges and emerging technologies in MMSs are used to identify potential future research domains and the results are listed in Fig. 12. The main categories of the MMS challenges and the modern technologies that can potentially address each challenge category are also summarized in the figure. The links between technologies and the challenges show the applicability of the respective technology to solve the corresponding challenge(s). In terms of future research, six main domains are identified, namely (1) scheduling and planning of MMSs, (2) factory operation, (3) new use cases and business cases, (4) standards and regulations, (5) training, and (6) sustainability. Domain 1 refers to the research on planning and scheduling at different factory levels from the planning of the supply chain and logistics to the MMS operational planning such as factory and shop floor layout optimization. Domain 2 mainly includes research on new manufacturing processes and equipment at component and system levels to help meet the MMS requirements summarized in Fig. 10. The domain can be branched into several research paths, which are listed in Fig. 12. For future work, it would also be worthwhile to explore new applications and use cases and develop business models for movable factories. This line of research can be covered under domain 3. Domains 4 and 5 deal with standardization and training in the field of MMSs, respectively. Finally, Domain 6 can cover research towards sustainability of MMSs such as Life Cycle Analysis (LCA), research on recyclable manufacturing material, waste management, and exploring energy-efficient technologies. The proposed research agenda on MMSs facilitates their realization and contributes to several key expected impacts such as enhanced local employment



Domain 1: Scheduling and Planning in MMSs

- Modelling, management, and optimization of dynamic/mobile supply chains for MMSs (e.g. optimized routing and navigation in movable factories)
- Shop floor and production planning
- Data analytics and transformation of information into knowledge for decision making

Domain 2: Factory Operation

- Scalable, flexible, and reconfigurable manufacturing processes for movable factories
- Innovative manufacturing equipment at component and system levels
- Manufacturing processes adaptable to a range of materials and equipment
- New autonomous manufacturing processes (including methods for human-robot interactions) and increasing current automation levels
- Effective system integration and coordination practices

Domain 3: New Use Cases and Business Cases

- Exploring new use cases and business cases for MMSs

Domain 4: Standards & Regulations

- Standardization of manufacturing procedures such as quality assurance, inspection, and waste management
- Effective standards & regulations for transportation of movable factory
- Health and safety standards related to personnel safety, risk assessment, ergonomic design, etc.

Domain 5: Training

- Effective frameworks for training regarding operation and safety of MMSs
- Application of advanced technologies such as VR/AR for personnel training

Domain 6: Manufacturing sustainability

- Life Cycle Analysis (LCA) of movable factories
- Energy-efficient manufacturing systems
- Effective waste management procedures
- Recyclable manufacturing/construction material

Fig. 12. Summary of the research gaps, opportunities, and potential future research directions.

and economic growth, sustainable competitiveness through the application of advanced technologies, and manufacturing sustainability.

6. Conclusion

This review presents a systematic concept literature review of movable factories. The background, definition, benefits, life cycle, related manufacturing concepts, literature taxonomy, requirements, use cases, challenges, and opportunities of the movable factories are reviewed through different sections. The literature review includes publications within the period 2000-2022 in well-established scientific databases. Overall, 23 keywords were considered as search strings, and the results of the review are formed based on 105 records (journal and conference papers, reports, dissertations, etc.) in addition to a small industry survey regarding the applications.

The review presents the historic overview of the movable factory, which shows that the concept was put forward in 2005 and since then, it has been considerably developed through the introduction of new use cases, application to SMEs, and the latest building-related mathematical frameworks for simulation/optimization studies. As highlighted by the literature, the main characteristics of movable factories include mobility, speed, and flexibility. The changes that these new characteristics will introduce to the manufacturing life cycle and the comparison with the life cycle of the fixed factories are discussed in the paper. The benefits and opportunities of using movable factories such as faster responses to requirements changes, high CapEx return, sustainability benefits, etc. are also elaborated. Regarding the latter point, the review specifically highlights the improved performance in terms of effort, time, and cost of transportation. In addition, the review draws a comparison between the FiaB, MMS, and other related manufacturing concepts. The comparison is based on eight manufacturing characteristics such as mobility, speed, modularity, and changeability.

The use case analysis found 16 different application domains in the context of MMSs. The review further breaks down the three main characteristics of movable factories into eight different requirements and examples are provided about how each requirement should be met. The review discusses the main challenges to the implementation and operation of the MMSs. All key challenges are identified and classified in six categories each covering a related manufacturing aspect such as human resources, equipment, logistics, and manufacturing economy. Moreover, the possibility of applying emerging manufacturing technologies such as digital twins, IoT, and additive manufacturing to the MMSs is explored and potential applications are suggested. The review ends with a conceptual framework that lists all potential future research opportunities within the movable factory context.

In terms of the limitations of this review, we should be fair to point out that the review is confined to the literature that is available in English and published after 2000.

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Conflict of interest

The authors declare that they have no conflict of interest.

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