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A review of movable factory sustainability: a triple bottom line perspective

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Abstract

This paper investigates the sustainability of movable factories, focusing on economic, environmental, and social factors. A structured literature review was conducted, and content analysis was subsequently used to analyze existing research, identifying key themes related to the sustainability impacts of movable factories. Findings indicate that movable factories can positively impact economic sustainability mainly through reduced costs and increased demand responsiveness. Additionally, they can contribute to environmental sustainability mainly by reducing emissions and resource consumption. For social sustainability, movable factories primarily offer opportunities for economic development and improved employee welfare. However, negative impacts, such as increased production network complexity, are also identified. Even so, limited data on the negative impacts on environmental and social sustainability limit insights. Overall, movable factories hold promise for enhancing manufacturing sustainability, but their feasibility and potential benefits should be evaluated case-by-case.

Keywords: Movable factories; triple bottom line; sustainability; manufacturing; literature review

1 Introduction

Today, manufacturing companies face challenges due to uncertain and volatile market conditions, including trade barriers, geopolitical conflicts, and climate changes [1], leading to rising logistics costs and disruptions in operations. These challenges significantly risk negatively impacting production networks and reducing competitiveness for the affected manufacturing companies. At the same time, sustainability has become more important for manufacturers, driven by environmental concerns and regulatory pressures. Sustainability practices help manufacturers reduce waste and emissions, which offers a competitive edge in the market [2]. Movable factories present a flexible solution to these challenges. Unlike traditional factories fixed to a single site, movable factories are designed for flexibility and mobility, allowing them to be set up quickly in different locations [3]. By enabling the relocation of production, companies can adapt to demand changes [4], reduce transport costs [5], and improve economic and environmental sustainability in uncertain markets [6]. Movable factories positively impact sustainability factors, such as reducing transport costs and allowing companies to relocate production, facilitating adaptation to changes in demand. However, sustainability is a complex phenomenon including numerous factors, especially considering the triple bottom line (3BL) perspective (i.e., economic, social, and environmental factors) [7]. At present, there is a lack of summarization of the various implications of movable factories on economic, social, and environmental sustainability. Hence, this paper aims to investigate the sustainability of movable factories and how they impact manufacturing companies' sustainability, adopting a broad perspective covering economic, environmental, and social factors.

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The paper is organized as follows. Section 2 reviews related research on sustainability and movable factories. Section 3 describes the methodology applied to this study and presents bibliometric insights. Section 4 presents findings from the data analysis. Section 5 discuss the findings of the study and Section 6 conclude on the findings and present avenues for further research.

2 Related research

2.1 Sustainable manufacturing

Various definitions of sustainability exist; however, one of the most prominent stems from the Brundtland Commission's [8] definition of sustainable development is famously described as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* Although sustainability has been a continuous discussion ever since, it remains a significant challenge. To exemplify, in the latest Europe Sustainable Development Report [9], most of the European countries' progression of the sustainable development goals (SDGs) are summarized. This summary indicates that many of the goals are still far from being reached, whereas, for instance, a staggering 25 out of 37 countries still face significant challenges in terms of reaching responsible consumption and production [9]. This calls for further efforts, especially in the industrial sector, where realizing sustainable manufacturing is critical. Sustainable manufacturing can be defined as *"the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources. Sustainable manufacturing also enhances employee, community and product safety."* [10]. The above definition emphasizes all three core parts of sustainability, also known as the triple bottom line, which was introduced by Elkington [7]. Achieving sustainable manufacturing might thus reduce negative environmental impacts, develop global social welfare, and contribute to economic growth [11]. However, achieving sustainable manufacturing is a complex task wherein various factors must be considered simultaneously.

2.2 Movable factories

Several concepts relate closely to movable factories [3] one of the earlier ones being the factory-in-a-box [12]. Stillström and Jackson [12] introduced the concept of production systems made up of sufficiently compact production modules that could be moved around, regardless of whether the destination was on-premise or to a different production site, possibly even abroad. A recent study by Kazemi et al. [3] investigated the conceptual foundations of movable factories and compared different types of movable production systems. They differentiated whether mobility was internal (e.g., production equipment relocating within the same facility), external (e.g., container-based production systems relocating between geographically diverse production sites), or a combination thereof. Fundamental to the concept of movable factories is that they are not fixed and, therefore, may respond to changes in needs by moving entire production systems, or elements thereof, to other locations [3]. To summarize, movable factories can be defined as production systems composed of compact, transportable modules that can be relocated either within the same facility or between geographically dispersed sites to adapt to changing demands.

Several studies have linked the ability to relocate production to sustainable manufacturing practices, such as the economic benefits of movable factories [13], the potential for lower negative environmental impacts through reduced transport needs of products [6], or the social benefits of movable factories [14]. Some have even integrated multiple perspectives by providing a summary overview of the potential benefits of movable factories [3]. However, their discussion focuses mainly on economic and environmental sustainability. Furthermore, while positive effects of movable factories on the sustainability of manufacturing companies have been identified, adverse sustainability effects could be associated with the relocation efforts of these factories.

In summary, current studies are limited in their perspectives on sustainability in two critical areas: (1) they fail to provide a comprehensive overview encompassing all three dimensions of the 3BL, and (2) they do not emphasize a nuanced view of the benefits and challenges of movable factories. Therefore, the research question addressed in this paper is:

"How do movable factories support economically, environmentally, and socially sustainable manufacturing?"

3 Methodology

The literature review reported in this study has followed the generic four-phase process described by Snyder [15]. During the design of the review (phase 1), familiarity with the topic was acquired through a review of initially identified literature as proposed by Hart [16]. The results of this phase are partly reported in Section 2. To further increase the quality of the review performed, a review protocol was established [17]. Excerpts from the review protocol are shown in Table 1.

Table 1: Excerpt from the review protocol of this study.

Review design parameters	
Databases searched:	Elsevier's Scopus and Clarivate's Web of Science
Period searched:	2000 - 2024
Language:	English
Search scope:	Title, abstract, and keywords
Inclusion criteria:	Reporting sustainability-related impacts of movable factories, geographical movement of production units

The search string used for this literature review is: *(movable OR moveable OR portable OR transportable OR on-site OR pop-up OR mobil*) NEAR/1 (factory OR factories OR "production unit*")) OR ((movable OR moveable OR portable OR transportable OR on-site OR pop-up OR mobil*) NEAR/0 (production OR manufacturing)) OR ("factory-in-a-box" OR "factory in a container")).*

In phase 2, the review was conducted, and screening of the identified literature was done according to a four-step process comprising activities and results, as shown in Figure 1.

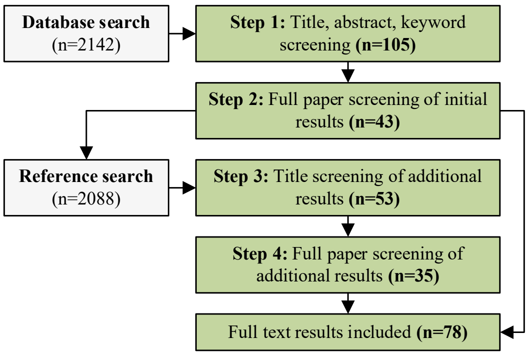

Figure 1: Literature identification and screening process.

The analysis of the literature (phase 3) is based on a hybrid deductive-inductive method of analysis has been adopted. First, the deductive part is the formation of high-level themes from the 3BL sustainability dimensions. These themes form the boundaries of the subsequent inductive analysis, where specific themes are formed by aggregating multiple data extracts (i.e., text, figures, or tables) with shared meaning from the included studies. This latter part of the data analysis is based on the qualitative content analysis method. To ensure the rigor of the analysis, this study has adopted the four-step process of Kleinheksel et al. [18], involving (1) identification of units of meaning, (2) labeling of similar units with a code, (3) grouping of similar codes into categories, and (4) describing related categories with themes.

Finally, writing the review (Phase 4) is documented in this study.

3.1 Bibliometric sample statistics

The publication year distribution for the 78 papers included in this study is shown in Figure 2. Although the literature search period spanned from 2000 and onwards, the first decade

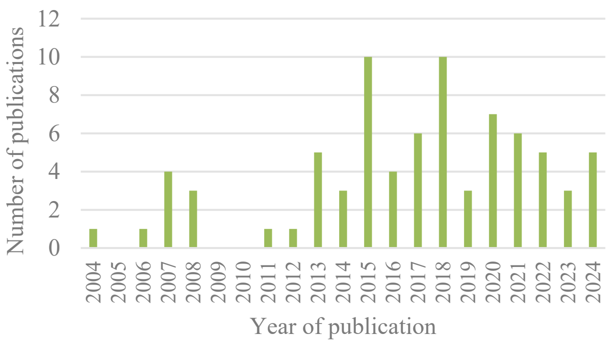

Figure 2: Publication year distribution for the 78 papers included.

covers only 12 % of the publications included, with the second decade covering 55 %. The publication distribution indicates an upward trend, indicating that the research on the topic is increasing. Of the 78 studies included in this research, 55 are journal articles, 22 are conference papers, and 1 is a book. The most frequent publication outlets are the Journal of Cleaner Production (6); Sustainability (5); and Technology in Society, Journal of Manufacturing Systems, and European Journal of Operational Research, with 3 publications each.

4 Sustainability of movable factories

This section details the findings related to the three sustainability dimensions of the 3BL framework.

To provide a nuanced perspective on how movable factories impact the sustainability of manufacturing companies, both positive and negative effects are of interest. Figure 3 provides an overview depicting the distribution of data extracts related to each sustainability dimension.

Evident from Figure 3 is the nearly non-existent sample of

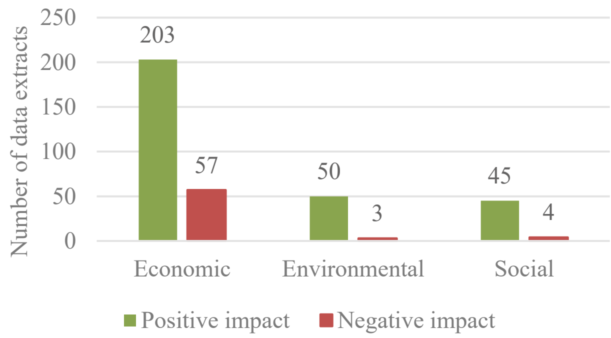

Figure 3: Distribution of data extracts from reviewed literature mentioning positive and negative impacts of each sustainability dimension.

data extracts focusing on negative impacts related to movable factories' environmental and social sustainability. Even when accounting for negative impacts being less prevalent in the dataset for all three sustainability dimensions, environmental and social sustainability are comparatively underrepresented, with only 5,6 % and 8,1 % of data extracts, respectively. This contrasts with economic sustainability, where 21,9 % of data extracts mention the negative impacts of movable factories.

In the following Sections 4.1 to 4.3 findings related to impacts for each sustainability dimension are presented. However, due to insufficient data available for negative impacts related to environmental and social sustainability, a graphical overview is only presented for negative effects related to economic sustainability (see Figure 5).

4.1 Economic sustainability

The 15 most prevalent themes with a positive impact on economic sustainability are listed in Figure 4.

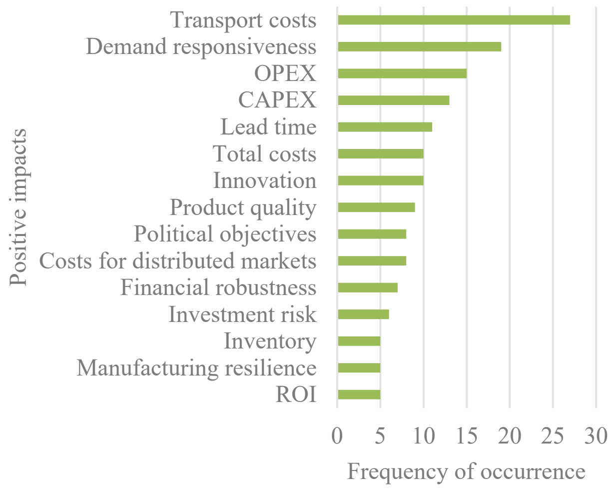

Figure 4: The 15 most prevalent economic themes with positive sustainability impact. (OPEX: operational expenses, CAPEX: capital expenses, ROI: return on investment).

The most frequent theme identified in the literature relates to reducing transport costs. A significant contributor to transport cost savings is the physical location of factories closer to customers. This naturally reduces the distance traveled for the finished product but also benefits products that take up significantly more volume compared to their comprising input materials, such as solar panels [5] or wind turbines [19], and vice versa for bio-oil, which is produced from voluminous biomass [20]. Proximity to customers furthermore has a positive effect on lead times [21,22]. Demand responsiveness is another prevalent theme in literature. This relates mainly to the rapid relocation of production facilities to the location of demand [23], the ability to rapidly accommodate needs for capacity changes [22], or the improved ability to make late product changes [24]. Using movable factories also positively affects total costs and, more specifically, operating and capital expenses [25]. Other notable benefits of movable factories include improved product quality due to, for example, reduced risk of cross-contamination [26], facilitating manufacturing innovation through alternative equipment procurement strategies [21,24], or facilitating the accommodation of political objectives [27], such as local content requirements [24].

Movable factories also present downsides, as highlighted in Figure 3, and Figure 5 expands upon these by listing the 11 most prevalent themes negatively impacting economic sustainability. Lower total costs, capital expenses, and operating expenses were identified as frequent positive economic impacts of movable factories in Figure 4. However, they also rank among the most prevalent adverse effects. Higher total costs can occur from a loss of economies of scale seen with movable factories [22,28]. Higher CAPEX of movable factories is a challenge for low-volume operations [28] and biomass processing facilities [20,29]. Delays in production start due to relocations [19,21] as well as costs associated with moving production facilities [6,21] are further economic challenges of movable factories. Such frequent

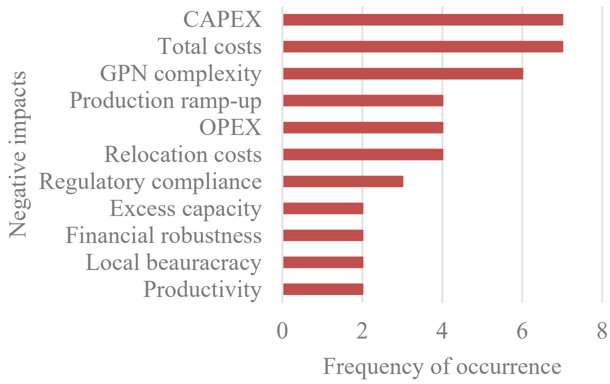

Figure 5: Frequency of 11 most prevalent economic themes with negative sustainability impact identified. (GPN: Global production network).

changes to the production network likewise increase the complexity of operating these [21].

4.2 Environmental sustainability

The lower presence of environmental sustainability themes in the dataset implies a lower number of themes with some prevalence. Figure 6, therefore, includes only the themes with

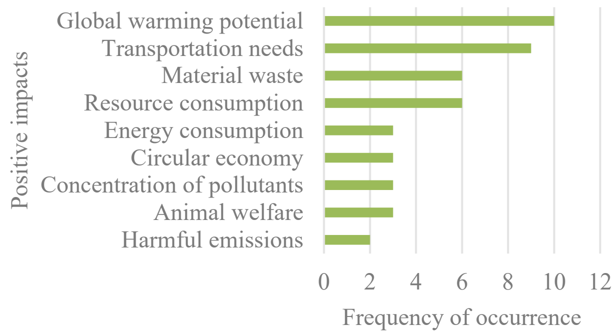

Figure 6: Frequency of the nine most prevalent environmental themes with positive sustainability impact.

multiple occurrences, resulting in nine themes.
Reduction in global warming potential through lower emissions of especially CO2 is the most frequently identified positive environmental impact of movable factories. Most reductions in CO2 emissions relate to reductions in transport of goods or materials [14,23] due to proximity to supply chain partners [26]. Other transport-related positive impacts stem from a reduction of non-value-adding transport, such as between centralized production facilities and distribution centers [30]. Lower waste generation in agricultural production [31] and lower material and energy consumption due to smaller production equipment [32] contribute to the positive environmental impacts of movable factories. Also relevant is the potential to reduce concentrations of waste and harmful materials due to the distributed nature of movable factory production networks [33] as well as the potential to improve animal welfare due to lower transport-induced stress [26] or harm [34]. The limited data concerning negative impacts on environmental sustainability, as shown in Figure 3, means that no themes have been formed. Even so, increased

energy consumption from long-distance data transfer was a potential challenge for movable factories [34].

4.3 Social sustainability

Social sustainability is the 3BL dimension with the least prevalence in the reviewed literature. Only eight themes have been identified with two or more occurrences, as shown in Figure 7. The most prevalent theme supporting social sustainability is the potential for movable factories to promote economic development in fragile or developing regions. Movable factories can benefit local populations by providing jobs in under-developed areas [35] and maintaining value creation locally [36], thereby supporting the development of local economies [26,33]. Utilizing movable factories enables the automation of otherwise manual processes, reducing worker load [32] and unfavorable ergonomic movements [12]. Movable factories are also found to promote diversity in employment [14], especially across genders [36] and wealth groups [37]. General improvements to the quality of life of local populations [31] and improved access to essential services and goods, such as medicine [38] are potential positive effects for the local community enabled by movable factories. The often lower cost of movable factories contributes to enabling cooperative enterprises [34]. Although insufficient data is available to construct themes for negative impacts on social sustainability, notable negative impacts include limited transfer of jobs to decentralized facilities and potential challenges in ensuring decentralized plants adhere to rules and regulations [34].

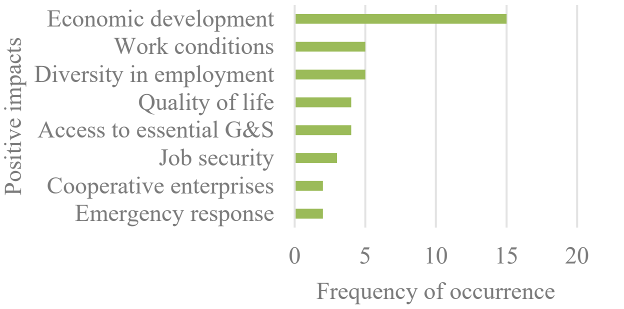

Figure 7: Frequency of the eight most prevalent social themes with positive sustainability impact. (G&S: goods and services).

5 Discussion

This study has identified multiple themes of primarily positive impacts on economic, environmental, and social sustainability enabled by movable factories, making them relevant for companies seeking to improve their manufacturing sustainability.

Positive effects on economic sustainability are especially widely reported in the literature, as shown in Figure 3. Several findings correlate well with previous studies, such as those by Kazemi et al. [3] who identified several positive impacts, although primarily related to economic and environmental sustainability. However, since most findings highlight the positive effects of movable factories, there is a risk of presenting an overly optimistic view of them due to the limited evidence of their challenges, especially for environmental and social sustainability. Moreover, the prevalence of themes is based purely on their frequency in the dataset and, therefore, does not necessarily reflect the actual magnitude of the impact.

Movable factories may support sustainable development for manufacturers, but their limitations should be considered when evaluating their feasibility. Potential benefits and drawbacks should be evaluated case-by-case, evident by the duality of several economic sustainability themes, where both positive and negative impacts for the same theme are identified, such as for CAPEX and total costs.

The reported sustainability impacts are not differentiated based on whether they originate from empirical studies or simulations or represent conceptual impacts of movable factories. Differentiating findings by study type would enhance understanding of their practical applicability. However, the potential of implementing movable factories is expected to vary significantly between manufacturers.

The identified sustainability benefits span multiple phases of a production system's life cycle, including operational benefits from lower CO2 emissions due to reduced transport needs or benefits in the start-up or reuse phases due to their re-deployable designs. Even so, challenges may be present, such as the planning and design of a movable factory, which can be complicated due to space or infrastructure limitations. Additional benefits or challenges are expected to be identifiable from the findings of this study.

Although this study has separated sustainability impacts according to the 3BL dimensions, it is recognized that impacts in one category may influence the others, both positively and negatively. For example, reduced transport activity can lead to a dual benefit: decreased costs and reduced carbon emissions, demonstrating a synergistic effect.

Lastly, while the rigor and quality of the data analysis presented in Section 4 have been strived for through well-recognized methods, the formation of themes is inherently subjective as it relies on the domain knowledge and data interpretation of the responsible coder [39].

6 Conclusion

This study has reviewed and analyzed extracts from 78 papers indicating that movable factories can significantly impact manufacturing companies' sustainability. While economic sustainability is the primary focus, environmental and social considerations are also relevant. The main findings for each sustainability dimension are:

Economically, movable factories can reduce costs mainly through lower transportation, operating expenses, and capital expenses. They also provide responsiveness to market fluctuations. However, increased production network complexity and potential delays in production start can offset these benefits.

Environmentally, movable factories can contribute mainly to reduced carbon emissions and more efficient resource use.

Socially, movable factories offer opportunities for economic development, especially in developing or fragile regions. Potential benefits further include improved employee welfare and more equitable employment practices.

It is important to note that although negative environmental and social impacts have been identified, the data is too limited to understand these issues comprehensively.

Lastly, the findings of this study indicate that movable factories can positively impact several phases of a production system's life cycle.

6.1 Future research

From the discussion in Section 5, the following relevant avenues for future research have been identified:

- Investigating the challenges and limitations of movable factories, especially regarding environmental and social sustainability.
- Explore contradictions in economic sustainability themes (e.g., higher CAPEX and lower total costs or vice versa).
- Investigate synergistic effects where impacts on one sustainability dimension influence others (e.g., achieving cost reductions and carbon emission concurrently).
- Differentiate sustainability impacts based on study types (e.g., empirical vs. simulated vs. conceptual) to enhance knowledge of the practical applicability of movable factories.
- Investigate life cycle benefits and challenges to assess manufacturers' potential gains from adopting movable factories.

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