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Sustainability metrics for the Factory-in-a-Box paradigm: informing early business case

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Abstract

The factory-in-a-box (FIAB) is an emerging alternative to traditional manufacturing solutions. Reliability, rapid response and closeness to point of use are key system characteristics that create competitive advantage, or fulfil unmet needs, where traditional manufacturing solutions are not feasible. Since this concept is gaining commercial credibility, exploration of sustainability in early business cases has become an important consideration for supporting sustainable manufacturing innovation in line with the UK net zero ambitions. This paper investigates appropriate sustainability metrics for informing an early business case for FIAB applications and provides a review of relevant sustainability indicators, amongst others. Further, a multicriteria decision making approach is proposed for assessing an early business case for FIAB. Lastly a use case of a real-world FIAB application is demonstrated showcasing business case sustainability assessment.

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1. Introduction

Factory-in-a-box (FIAB) is a manufacturing system that originates from ideas of redistributed manufacturing [1] offering an alternative to traditional manufacturing systems. FIAB has been explored as a strategic capability that can provide on demand, flexible and reconfigurable capabilities [2]. Several examples of the system exist as demonstrators [3], mainly focusing on applications in rapid response scenarios like natural disasters and pandemics [4], or redeployability where it is important to create capability on demand [2]. As

these manufacturing systems gain presence in an industrial arena, building an understanding for the business case for such applications becomes an important component in maturing its implementation.

One of the key considerations for successful implementation is consideration of different feasibility aspects and commercial objectives. For example, there is a need for manufacturers to reduce environmental impact of manufacturing activity across sectors to support decarbonisation ambitions. Therefore, it is important to understand what wider considerations should be assessed when developing a rationale for implementing novel

manufacturing systems like FIAB. The early business case can be an important indicator of performance, cost and sustainability of newly planned industrial systems. Therefore, this paper investigates how the FIAB concept can be assessed using wider sustainability indicators.

This paper is structured as follows: the sustainability indicators that can inform early business case are explored; a conceptual framework for FIAB assessment is proposed; and lastly a practical demonstration of the conceptual framework and discussion around its usefulness in informing new manufacturing system developments from a sustainability perspective.

2. Literature Review on Sustainability indicators for FIAB

FIAB is a form of Redistributed Manufacturing (RdM) [5], where production takes place in smaller, local, facilities that are closer to the points of demand [6]. The study of the impact of RdM on sustainability has gained momentum over recent years. In a review of sustainability in redistributed manufacturing [7], the author reports that the shift towards an RdM paradigm could potentially improve the sustainability of manufacturing systems through circularity and increased product longevity. In a review of the movable factory paradigm, the authors of [8] report that movable factories can have a favourable impact on sustainability, particularly in terms of greenhouse gas emissions, due to lower transportation needs. In [9], the authors discuss the prospects of massively distributed manufacturing, which is an RdM system that operates within a large network of stakeholders. The authors argue that adopting a massively distributed manufacturing paradigm could have a positive impact on environmental sustainability due to localised production. The authors of [10] also propose that distributed manufacturing in urban areas, when coupled with advanced technologies such as blockchain, can have positive environmental impacts, particularly with respect to circularity, echoing the findings of [7]. However, there is limited literature linking FIAB directly to sustainable outcomes. Nor are the overall motivations for the FIAB concept perceived as sustainability focused [11]. However, some FIAB characteristics can have a positive impact on industrial sustainability overall [11]. The authors in [12] suggest that

drivers first is a fundamental assumption when considering sustainability of systems. Therefore, being able to address sustainability in the early business case can provide an indication of driving system development towards achieving sustainable outcomes.

Table 1. Review of sustainable manufacturing indicators based on [15,16,17,18]

System Level	Environmental	Financial	Social	Performance
Operations/ processes	Energy usage Material consumed Waste rate Water consumption	Cost of process	Health and safety Technology Development	Excess Capacity Productivity Product quality Lead time
Facilities	Building energy consumption Rate of renewable energy Waste from facilities	OPEX / CAPEX Transport costs Total cost	Jobs created Jobs security Working hours Working conditions	Production ramp-up Inventory
Systems	Energy self-sufficiency Global Warming Potential Concentration of pollutants Animal Welfare Circular Economy Harmful emissions Transportation needs Material waste Resource consumption Harmful Emissions Energy shared Waste generated	Return on Investment (ROI) Whole Lifecycle Cost Internal rate of return Relocation costs Cost of distributed markets Financial robustness Investment risk Whole Lifecycle Cost	Diversity Quality of life Social benefits and security Social responsibility Economic Development Access to essential goods and services Cooperative enterprises Emergency response Freedom of association and collective bargaining Child labour Delocalisation and migration Access to resources Access to immaterial resources Cultural heritage Safe and healthy living Respect of indigenous rights Community engagement Secure living conditions Equal opportunities / discrimination Social benefits/ social security Employment relationship Sexual harassment Smallholders including farmers Fair competition Promoting social responsibility Supplier relationships Respect of IP rights Wealth distribution Feedback mechanism (for consumers) Consumer privacy Transparency End-of-life responsibility Public commitment to sustainability Contribution to economic development Prevention and mitigation of armed conflicts Technology development Corruption Ethical treatment of animals Poverty alleviation Education provided to local community Health issues for children as consumers Children concern regarding marketing practices	Time to redeploy Time to respond Demand responsiveness Innovation Political objectives Manufacturing resilience Global production Network (GPN) Complexity Regulatory compliance Productivity Local bureaucracy

Sustainability considerations span across areas of manufacturing operations, supporting facilities and surrounding buildings [13]. On the other hand, the authors in [14] recognize sustainability indicators on product, process and system levels. For FIAB, the main objective is redeployability as well as rapid response. It is a critical functional role at a system level.

Fig. 1 provides an overview of the combination of these considerations.

Sustainability indicators in manufacturing have been extensively covered in the literature and the summary of them can be reviewed in [15][16][17][18]. In [15] authors review existing literature focusing on indicators for sustainable manufacturing through mutual similarities where they recognize five dimensions: environmental stewardship, economic growth, social well-being, technological advancement, and performance management. On the other hand, [16] focuses on identifying key themes related to the sustainability impacts of movable factories based on literature highlighting indicators relevant to cost and value, materials and

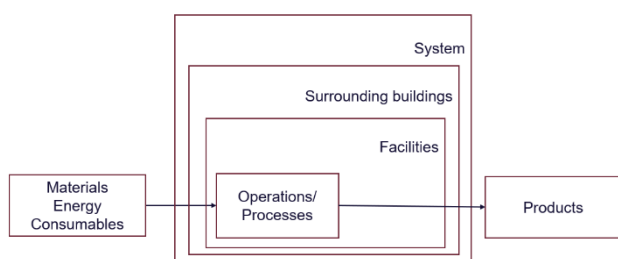


Fig. 1. Summary of sustainability considerations applied across different levels of manufacturing system context

when looking at sustainability considerations, one must take these from the perspective of values / objectives assumed at a system design or business model planning stage, considering solutions for sustainability first before looking at other system solutions. Following this logic, understanding sustainability

processes, transportation, system performance at operational and business model levels, as well as key social indicators. Further, [17] provides an overview of social indicators used in the wider social lifecycle assessment (LCA) context highlighting key categories, such as: worker, local community, value creation actors, consumers, society and children. This systematic approach provides 40 different indicators. In [18] a roadmap towards sustainable production is presented where KPI definition is highlighted as a key first step in practical strategy development. The KPIs focus on environmental indicators – energy, waste and emission related. The framework then provides insight into technologies and practices that can meet the aforementioned indicator and provides insight into assessment of the initiatives from an implementation and impact perspective leading to timeline-based roadmap development. Building on these works, as well as understanding the FIAB at different system levels, the sustainability indicators from aforementioned sources are presented in Table 1.

These indicators can form a comprehensive consideration towards building a holistic view on the system feasibility and considerations towards sustainability; although, [20] points out that economic and social indicators are less mature. Due to the sheer number of indicators that can be considered, there is a need to prioritize these indicators based on the context of the business case.

There are different methods of sustainability assessment that provide prioritization opportunities. The authors in [18] proposed a conceptual framework for how manufacturers can transition to sustainable production focusing on system improvement and technology transformation. Further, [20] provides a review of LCA as a preferred method for sustainability assessment. On the other hand, [19] provides review of various multicriteria decision making (MCDM) approaches used to achieve sustainable manufacturing that uses fuzzy-based single model approaches, and [21] provides another MCDM framework where subjective and objective weighting techniques allow normalisation and aggregation of different sustainability criteria. To date, only one FIAB sustainability assessment using LCA has been conducted [5] and no literature specific to the concept of FIAB sustainability assessment have been published. Therefore, this paper focuses on exploring FIAB sustainability assessment for informing the early business case using MCDM approach. The next section provides a conceptual framework build based on the MCDM approach and mapping of the sustainability criteria relevant to FIAB.

3. FIAB Sustainability Assessment Conceptual Framework

The proposed framework is centered on FIAB features sustainability indicators that can be captured across the manufacturing system characteristics together with a MCDM methodology, which can be used as a basis towards capturing evidence for early concept assessment as well as enabling evaluation of concept options. The following methodology is proposed in Fig. 2.

The intention is that the framework provides a means of capturing the scope of a business case for a FIAB application,

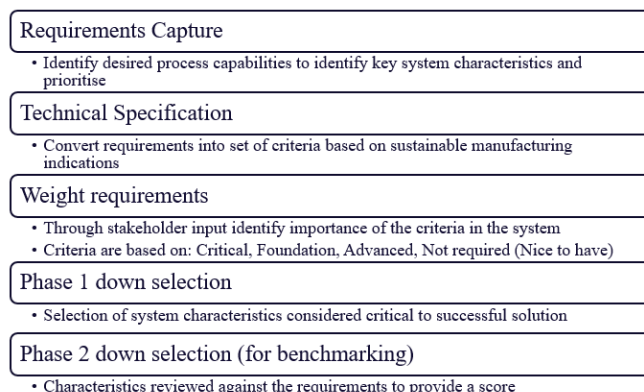


Fig. 2. FIAB Sustainability Assessment Conceptual Framework based on MCDM

as well as a benchmarking capability for different options of the manufacturing system application. In this case, the approach used in [22] has been adapted based on MCDM approach. The tool has been developed in Microsoft Excel software capturing the process defined in Fig. 2. The first step is based on the notion of requirements definition. It aims to capture process capabilities and performance requirements for the manufacturing system. In case of FIAB, typically responsiveness or redeployability functional requirements will drive the prime system functionality. Next, the requirements are translated into a set of criteria. This is based on selecting appropriate sustainability indicators driving the criteria. The indicators in Table 1 provide a spectrum of possible options. In this case, the evaluation of FIAB, as with any other manufacturing system, needs to focus on inclusive criteria that will meet functional and performance, viability and sustainability requirements.

The selected criteria are then weighted. Weighting through stakeholder engagement by point allocation has been selected in this case but a range of other options, such as ranking method, swing method, SMART technique, could be appropriate depending on the scope of the analysis. The concepts defined for FIAB systems are then scoped based on the defined criteria, and weighting is allocated based on the stakeholder score to provide a concept evaluation. The next phase focuses on identifying non-viable concepts based on meeting critical criteria. This means that criteria that were defined as “critical” become non-negotiable and if the proposed concept does not meet it, it is disqualified from the analysis. Lastly, the remaining concepts are reviewed, and a score is provided that is then broken down into weighted scores. This allows for review of the concepts based on the weighted criteria as a whole and on a per criterion basis.

The next section provides a use case of the FIAB application assessment for a packhouse-in-a-box, as defined in [1].

4. Use Case

The case study explored in this section is based on the concept for factory in the box investigated at the Manufacturing Technology Centre. The case study focuses on supporting introduction of manufacturing-led methods in the agricultural sector. The challenge is to evaluate relevant use cases at the early concept development stages of project lifecycle to inform viability of the concept and provide insights into key “hot spots”.

Packhouse-in-a-box, as presented in [5], is a manufacturing concept for supporting in-situ packing at farms involved in seasonal fruit picking. It provides a redeployable service in the box that contains a washing station, a pick and place robot, a vision system that enables produce grading, and a packing station. The aim is to minimize the fresh produce damage throughout the distribution system – from farm to point of sale – by providing a cleaning and packing service in a close picking proximity and reducing the number of handlings required.

This use case examined a traditional value chain and packhouse-in-a-box concept. The scope covers a season of apples collection (August – September – 60 days), from 3 locations where 30 tonnes of apples a day are collected daily.

The key requirements identified for this activity are:

- 30 tonnes of apples collected every day
- Focus on maximizing product quality
- Available on-demand

Key assumptions for traditional value chain are:

- Apples are collected daily requiring 4 lorries to pick up (7.5 tonnes per lorry)
- From farm, the apples are transported to: a local distribution centre, central washing and packing facility, regional distribution centre, shops/ point of sale
- There is a 30% loss due to damage in various transport routes

Packhouse-in-a-box:

- Apples are collected, washed and packed at the farm
- Packed apples are moved to regional distribution centre and the point of sale by 4 lorries per day (7.5 tonnes per lorry)
- There is a 10% loss due to damage in transport routes
- The system redeployment routine consists of: a set up time of 4 hours, cleaning and maintenance of 4 hours, transport time between sites of 2 hours and requires 1 operator over this time
- Power supply from the grid or through combination of diesel and solar energy is used to power the system

Table 2 provides an overview of the key indicators captured for the two scenarios. Since the assessment looks at economic activity that aims to maximise product retention, as well as evaluate the impact to local community, the selection of the KPIs covers overall costs, time to provide service, value retained in community and resources used.

Table 2. Summary of key indicators selected for this study

KPI	Traditional	Packhouse in a box
Total Processing Cost	£18,000*	£23,076**
Transport Cost	£90,000 (all deliveries)	£30,000 (all deliveries)
Product Quality	1260 tonnes	1620 tonnes
Time to Redeploy	None if scheduled On demand within 1 day	10 hours
Wealth distribution	No incentive to local community	Gain of 20% more apples to end up in the farmer pocket
Health and Safety	0.5 incidents per 60 days *Not applicable at farm 5 in 1000 incidents per year	3 incidents per 60 days *Semi-automated system Requires connecting consumables 1 in 300 incidents per relocation
Global Warming Potential	61.7 kgCO ₂ e per tonne [16] Total: 77,700 kgCO ₂ e	13.13 kgCO ₂ e per tonne [16] Total: 21271 kgCO ₂ e
Waste Generated	5,400 tonnes of product	180 tonnes of product
Energy Consumption	975 kWh	1950 kWh
Water Consumption	1350 m ³	1350 m ³

*Cost of commercial apple sorting based on a volume of 18000 tonnes at £1 per tonne

**Cost of FIAB £2M over 10-year period

The key indicators for the study were weighted based on priority. Critical (weight of 25 points) for: Product Quality, Foundation (weight of 20) for Transport costs and Global Warming Potential, Advanced (10 points) for remaining ones. The indicators were then scored from 0-5 where the following capabilities have been assumed: no capability, some capability, good capability, very good capability and excellent capability. The summary of scores is presented in Table 3.

Table 3. Summary of scores for sustainability indicators assessment

Number of Scores	Current MODEL	FIAB Concept 1
Critical	7	10
Foundation	9	13
Advanced	9	9
Not Required	0	0
Total	25	32
Phase 1 Selection	Yes	Yes
Weighted Scores	Current MODEL	FIAB Concept 1
Critical	175	250
Foundation	180	260
Advanced	90	90
Not Required	0	0
Total	445	600
Total (critical and foundation)	355	510
Phase 2 Rank	2	1

The current model had 7 critical, 9 foundation and 9 advanced requirements, whereas the FIAB concept had 10 critical, 13 foundation and 9 advanced requirements. When it comes to weighted scores, the current concept score is 445 and FIAB score is 600. From the current assessment, the FIAB concepts scored better in Critical and Foundation requirements, and with applied weighing it is clearly the preferred option.

5. Conclusions

This paper focused on the exploration of sustainability indicators for early business case assessment for factory-in-a-box (FIAB) concept. As the literature in this area is limited, a review of sustainability and performance indications has been reviewed and collected alongside FIAB unique capabilities-redeployability and responsiveness.

Further, limited literature on business case assessments for FIAB has been found, and methods for sustainable manufacturing assessment have been reviewed to explore decision support options.

Next, a framework based on multi-criteria decision-making has been proposed, focusing on providing capability to assess holistic system KPIs to carry out comparisons of system options through a weighting and scoring approach. This method provides an approach towards holistic capture of different performance and sustainability requirements, and further assesses the options based on a scoring system. This approach is suitable for informing the early business case as the data maturity for this can be low or based on assumptions, but it allows quick identification of systems that are not suitable (not meeting critical criteria).

Finally, a concept of packhouse-in-a-box has been used to demonstrate the proposed methodology, providing an applied example of the apple distribution value chain focusing on improving product quality while balancing other indicators.

This paper contributes to a limited literature about the FIAB concept and sustainability focusing on identifying a suitable approach for early business case assessment.

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