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Moveable Factories for Leapfrog Manufacturing in an Industrial Economy

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Abstract: Moveable factories can enable leapfrogging of fixed industrial factories, and so make immediate contributions to global goals of more resilient sustainable manufacturing. Moveable factories bring into use diverse technological advances that reduce the number, size, and weight of machines needed to carry out manufacturing operations at points of supply and/or demand. However, fixed industrial factories continue to be the principal focus for development and application of new manufacturing technologies. At the same time, fixed industrial factories continue to be seen by policy makers around the world as the default option for developing prosperity: rather than as an old fashioned production paradigm to be leapfrogged over. In this paper, findings are reported from a case study investigating potential for moveable factories to bring leapfrog manufacturing to an industrial economy. This case study comprised literature review, interviews, and theoretical analyses. Study findings indicate that organisations in an industrial economy will consider moveable factories if fixed factories are not feasible, practical, or viable. By contrast, potential for improved efficiency and flexibility may not be sufficient to motivate a shift away from fixed industrial factories.

Keywords: industrial psychology; leapfrogging; manufacturing; moveable factories; technology diffusion

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1. Introduction

New manufacturing technologies continue to be channeled mainly into fixed industrial production under slogans such as Industry 4.0 and Smart Manufacturing [1,2], and fixed industrial production continues to be seen by policy makers around the world as the default option for increasing prosperity [3–5]. However, with increasing diversity in manufacturing technologies, which in some cases reduces spatial footprints of machines to a domestic scale, it is clear that these new opportunities not only to innovate the way goods are made, but the sites and systems those goods are made within. In this regard, moveable factories can enable beneficial leapfrogging of fixed industrial factories. Moveable factories bring into use diverse technological advances that reduce the number, size, and weight of machines and materials needed to carry out production operations [6,7]. Different moveable factories can involve different types of technologies depending upon what type of moveable production they are designed to carry out. For example, advances in robotics are important for enabling efficient flexible moveable handling of raw and processed materials [8]. Digitally-driven machines, such as multi-axis routers and 3D printers, are more relevant to production at point of demand [9]. In this paper, findings are reported from a case study investigating potential for leapfrog manufacturing with moveable factories in an industrial economy. The case study comprised literature review of the state-of-the-art in moveable factories, interviews with five organisations, and analyses applying different theories related to technology diffusion, industrial psychology, and leapfrogging.

The remainder of the paper comprises the following four sections: First, method is described. Then, results are presented. In the penultimate section, implications are discussed. In conclusion, principal findings are stated.

2. Methods

2.1. Review of the State-of-the-Art for Moveable Factories

The review encompassed moveable factories to improve production of established types of goods and enable production of new types of goods. These categories are derived from two main themes in the literature concerning distributed manufacturing. In particular, industrial organizations seek to increase the geographical distribution of producing established types of goods through smaller fixed factories [10]. Meanwhile, individuals involved in the maker movement, personal fabrication, social manufacturing, etc., seek to increase demographic distribution of manufacturing when producing new types of goods [11]. The review had to extend beyond review of scientific literature. This is because moveable factories for improving established goods are reported at company websites and in trade journals more than in scientific literature. For example, a company called The Can Van explains its mobile canning services for craft beers on its website and provides links to articles about the company in trade journals such as *Beverage World* [12]. Similarly, companies' advances in moveable roll forming technologies are reported in trade journals such as *Metal Construction News* [13]. Information about moveable factories enabling the production of new types of goods can be found in scientific journals that encompass production by consumers and in reports from high circulation media and broadcasting channels such as the BBC, *Newsweek*, *Popular Science*, TEDx, and *Wired*.

2.2. Interviews

Participants comprised a purposive sample of five organisations listed below [14]. The five different types of organizations represented a range from large urban authorities to small biotech groups. Thus, it was intended that the research could reveal a broad range of opinions about moveable factories.

- An urban area authority encompassing one large town, some suburbs, and some semi-rural land. The urban area had a current population of approximately 110 thousand people, and the population was forecast to grow.
- A non-urban area authority encompassing some 30 communities ranging from a few people to 400 people. The total population of non-urban area was approximately 4500 people. The population was not forecast to grow.
- A packaging company interested in considering new options to improve its production performance in the face of international competition. As described in the state-of-the-art review below, processing and packaging at points of supply are important applications for moveable factories.
- A biotechnology group seeking to improve established goods and enable new types of goods, with natural materials found in arid conditions. This organization was focused on production at the beginning of product lifecycles.
- A plastics recycling alliance of established companies seeking new ways to recycle plastics from manufactured goods. This organization was focused on production at the end of conventional product lifecycles.

All five types of organizations were provided with the same introductory information about moveable factories. Subsequently, they provided their opinions about the potential of moveable factories. In each case, interview responses were provided principally by one representative, who had the opportunity to take input from colleagues. The informant style of unstructured interview was used. Hence, the interviewer did not seek to control the interviews. Rather, interviewees freely expressed their thoughts and took the interviews in the directions that they chose. This type of unstructured interview can be contrasted to the respondent style of unstructured interview where the interviewer seeks to follow a more defined agenda [15].

2.3. Bases for Theoretical Analyses

2.3.1. Technology Diffusion

Theories range from determinism to domestication. Within technology determinism, technologies are causal agents that transform society without people having much control over that transformation [16]. By contrast, within technology domestication, people reject or accept and tame technologies through their own individual experiences. Metaphorically, technology domestication focuses on the progression of technological devices from being perceived as dangerous to being accepted as harmless, but not necessarily positive, in everyday life [17]. Between technology determinism and technology domestication is the social construction and social shaping of technology. This involves people formulating technologies through different types of engineers who develop technologies and who are influenced by their social contexts [18]. Common across these different theoretical positions are observations that different human perceptions about technologies' usefulness and ease of use influence whether organisations are innovators, early adopters, early majority, late majority, or laggards [19].

2.3.2. Industrial Psychology

Various types of preconceptions influence perceptions about technologies. Common sources of preconceptions in industrial psychology include competency traps, success traps, path dependencies, and lock-ins. Competency traps involve organisations focusing on competencies they are already expert in, even when new technologies make that expertise increasingly irrelevant [20]. Success traps involve a period of successful organizational performance leading to stale ideas about what makes success for all time into the future [21]. Ideas about the best course of action to take can become path dependent—even when better options become available [22]. Lock-in can follow investment in a particular competency or path because of the belief that there has already been too much invested to quit [23].

2.3.3. Leapfrogging

Theories concerned with leapfrogging encompass relationships between successful users of established technologies, those who have limited access to established technologies, and new technologies [24]. In particular, successful users of established technologies may have much less incentive to switch to a new technology than others who have limited access to established technologies. At the firm level, this can lead to creative destruction when those with limited access to established technologies create new attractive offerings by using new technologies to leapfrog over incumbents' offerings [25]. It has also been argued that regions and nations, as well as firms, can leapfrog [26]. The principle of leapfrogging over established technologies is also applied in the international development of, for example, mobile phone banking and renewable energy provision. Here, the focus is not initially on competition to get more wealth. Rather, the initial focus is upon enabling access to technical systems that can alleviate poverty [27].

3. Results

3.1. Moveable Factories

3.1.1. Limitations of Moveable Factories

There are many heavy manufacturing processes, such as converting iron ore into steel, that require too much energy and space to be carried out with moveable factories. In addition to heavy industrial processes, moveable factories are not well-suited to mass production of goods for nearby mass markets. However, as described in the following sub-sections, there are many other types of production that can be carried out successfully with moveable factories.

3.1.2. Moveable Factories to Improve Production of Established Types of Goods

Moveable factories are used to improve different stages of production of established goods. For example, they can be used to carry out the conversion of natural materials at sources of supply, including the conversion of fruit into juice, and livestock processing that reduces animal suffering. Such use of moveable factories increases efficiency by reducing the transportation of bulky crops and live animals. Overall, any upstream practices with moveable factories that reduce the number of times produce is handled and transported can reduce losses [28]. Simultaneously, flexibility is increased by the potential for moveable factories to travel to wherever raw materials are ready at a particular time.

In some cases, such as boxing fruit and vegetables at farms, moveable factories can be used immediately to carry out packaging operations. When raw materials cannot be converted and packaged at the same place and time, moveable factories can also be used to increase the efficiency and flexibility of packaging: for example, bagging loose materials at harbours, bottling wine at vineyards, and canning beer at craft breweries. Such use of moveable factories increases efficiency by reducing the transportation of processed materials to and from large packaging factories and increases flexibility by enabling packaging to be carried out on demand [12].

Further downstream, moveable factories can be used to produce at points of demand. Sophisticated assemblies can be made by moveable factories at construction sites, mineral mines, and military bases [29]. Moveable factories can be for specific types of production such as roll forming metal fascia, guttering, etc. [13]. Alternatively, moveable factories can be equipped for the manufacture of a diverse range of mechatronic assemblies using digitally-driven multi-axis routes and 3D printers [9]. An example of advanced mobile factories for food production is a moveable factory for making biscuits with added nutrients in Afghanistan [30]. The use of moveable factories at points-of-demand increases efficiency by, for example, reducing the transportation of volumetric assemblies. They increase flexibility by producing directly whenever and whenever there is demand. In all of the above examples, moveable factories are used to improve particular phases of production, while the remainder of production continues with fixed factories. In all cases, efficiency can be increased by disintermediation that reduces "middlemen", such as hauliers, between upstream suppliers and ultimate end-users [31].

3.1.3. Moveable Factories to Enable Production of New Types of Goods

In some cases, moveable factories can be used to enable production of new types of goods, including goods that end-users are involved in making themselves. Here, three examples are provided to illustrate the range of sophistication of new types of goods made with moveable factories. The first example is on-site conversion of the rubble from destroyed buildings into interlocking blocks that simplify construction processes. The second example is production of person-specific prosthetics away from medical facilities. The third example is the local production of motor vehicles. In all of these examples, end products are reimagined and reengineered for highly distributed local production by local people. However, it is important to note that moveable factories are enablers of local production by local people, rather than the focus of innovation.

Moveable factories for converting rubble into interlocking blocks are used to address the need for rapid construction following building destruction caused by earthquakes and wars. At the same time, they are used to deal with huge quantities of rubble caused by the destruction of buildings. The conversion process involves the crushing, filtering, and liquefaction of rubble into a mixture for making blocks. After preparing the mixture, the interlocking blocks are cast. Then, after preparing necessary ground work, blocks are stacked by hand. This involves inserting bamboo poles into the walls to provide extra stability. Similar in design to Lego bricks, blocks are stacked and interlocked without requiring cement or mortar. The whole process of rubble conversion, block casting, and building construction is designed to be carried out by local people who do not have any relevant previous experience [32].

With regard to production of person-specific prosthetics, this is just one of the 3D printing activities carried out at the scene of humanitarian disasters. Production of smaller simpler parts is also important. This is because parts, such as clips that close plastic sheeting for shower stalls, replacement pump parts, and latrine-cover hinges, can account for a sizable portion of goods brought into an emergency. Moreover, they can be critical for effective use of other much bigger goods such as tarpaulins. However, compared to other activities, 3D printing prosthetics is much more sophisticated. An example is a prosthetic hand 3D-printed in carbon fiber-reinforced co-polyester material for under 75 US Dollars (USD) on a 3D printer costing less than 2000 USD. Local people can be trained to produce prosthetics and are provided with 3D printers and materials to do so [33].

With regard to the production of new types of motor vehicles, websites are set-up for individuals to put forward their own vehicles designs and for individuals to vote for or against other individuals' vehicle designs. Subsequently, individuals can participate in the local assembly of vehicles at moveable factories. The number of votes for a vehicle design indicate the level of demand for a vehicle, and so the economic viability of beginning production. The break-even point for economic viability is reduced by engineering design of vehicles as kits for self-assembly in moveable factories containing digitally-driven machines and traditional hand tools [34].

In all three examples, efficiency is increased through the simplification of processes to enable individuals to participate in production. This involves application of very well-established techniques such as designing for part count reduction through parts consolidation using net shape manufacturing processes [35].

3.2. Interviews

3.2.1. Urban Authority

It was recognized by urban local authority that moveable factories could support increased value adding at farms, such as local processing and packaging for artisanal foods. However, the urban local authority saw very little potential in its region for the use of moveable factories to improve production in agriculture and food. There were three reasons for this opinion. First, regional production is organized efficiently for supply to bulk markets. Second, popular social practices are embedded in production, such as the regional sale yard for livestock being a meeting place for farmers. Third, regional production is profitable.

The urban local authority saw potential for job creation in its region by using moveable factories within Web-enabled highly distributed local vehicle production by individuals. In particular, the regions' expertise in making a wide variety of equipment, machinery, and vehicles was seen as having the potential to provide local resources for engineering design work necessary to transform individuals' vehicle designs into self-assembly vehicle kits. Moreover, companies making railway carriages and truck trailers have skills that can be applied to the fabrication of moveable factories for vehicle self-assembly. However, the enthusiasm of existing companies to initiate this new approach to vehicle design, manufacturing, and assembly was uncertain. Another alternative would be for individuals to set-up new Web-enabled business for highly distributed vehicle production. The urban local authority considered that there were more than sufficient computer skills in the region to enable the setting up of the necessary Web-enabled systems. If so, existing companies could provide engineering and components for vehicle kits on the basis of purchase orders from the new Web-enabled vehicle businesses. Thus, they could continue to operate as before within contract manufacturing, but with a new type of customer: Web-enabled start-ups for highly distributed vehicle production.

3.2.2. Non-Urban Authority

Similarly, the urban local authority saw very limited potential for use of moveable factories by companies in its regions involved in the production of equipment, machinery, and vehicles. Some of these companies are involved in component manufacturing, while others fabricate capital goods such as railway carriages and refrigerated truck trailers. By contrast, it was considered that there was some potential for moveable factories to improve production of construction goods such as roof trusses and wall panels. This is because they were being transported to local construction sites after having been made at distant factories in other regions. Thus, moveable factories could be used to enable efficient, flexible, on-site fabrication work and so increase local construction sector employment. The non-urban local authority saw many opportunities to improve production in agriculture and food. In particular, it saw opportunities to ensure that produce from its area could be given the highest level of organic certification. This could be achieved by all livestock and crop processing being done locally rather than livestock and crops being processed in distant factories without the highest level of organic certification. Thus far, agricultural and food production had been carried out within industrial production involving live animals being collected at set times and transported long distances. Hence, moveable factories could bring reduced animal suffering and opportunities to optimise production to suit animal growth, crop growth, etc.

The non-urban local authority saw many opportunities for job creation in its region by using moveable factories for manufacture and fabrication of new infrastructure capital goods such as solar arrays. Also, it saw many opportunities to shift from agriculture and food production within industrial mass production at distant fixed factories to local artisanal agriculture and food production.

3.2.3. Packaging Company

The packaging company saw limited potential for the use of moveable factories. There were general concerns about the potential time required to recalibrate the settings of sensitive machines after each trip between work locations. One suggestion from the company was to bring automated fruit package to farms by moveable factories. This was seen as an opportunity to address perennial challenges of their customers—farmers—trying to find enough human packers who were willing to travel out to farms and who were motivated to take care when packing fruit.

Although the packaging company saw limited potential for use of moveable factories, they did suggest that perhaps moveable factories could enable their customers to add more value at their farms. One possibility could be for fruit to be converted into juice at farms with moveable factories, and juice put into plastic bottles and/or cartons produced at farms with other moveable factories. Such production is possible because plastic bottle blow moulding machines and carton making machines are small enough to be transportable. At the same time, the transportation of required materials, such as plastic pellets and coated paperboard, is much more efficient than transportation of empty bottles and cartons. Although the company considered this as a possibility, they did not see it becoming a business priority for them in the foreseeable future.

3.2.4. Biotech Group

The biotechnology group saw much potential in using moveable factories to address the challenges of processing natural materials that are highly distributed across very large arid land areas. Typically, natural grasses etc. grow erratically in clumps across arid regions, rather than consistently in pastures. Hence, they cannot easily be collected with industrial harvesting methods. Furthermore, natural growths can be an important part of natural arid land ecosystems by stabilising sand and acting against desertification. Hence, they cannot just be ripped up—especially when roots can be extremely deep in order to find moisture. Due to ground undulations and softness, the cutting of natural grasses, etc., would be difficult to fully automate. Hence, moveable factories could at best support human cutters by providing tools for cutting, sharpening, carrying, etc. In addition, moveable factories could be used for sorting and compacting processes to reduce the transportation required to carry natural grasses, etc.

The biotechnology group could see potential for moveable factories to support artisanal production with natural grasses, etc. For example, seeds can be used in local production of foods, while grasses can be used in local production of woven products. Such goods could have some cachet because of the difficulty of cutting and working with natural material from arid regions. It was recognized that production of such goods would have to be preceded by marketing to establish a positive market identity for them.

3.2.5. Recycling Alliance

The plastics recycling alliance saw moveable production as being very advantageous for the beginning recycling of goods that are difficult to collect and transport to large recycling plants. Plastic bottles, for example, can quite easily be collected and transported when bottle return facilities are set up with small rewards for each bottle returned. By contrast, large billboard banners and signage include large quantities of plastics and are difficult to collect and transport. However, the plastics recycling alliance saw that billboard banners and signage could be ground up into particles locally using moveable autogenous milling machines. These milling machines consist of rotating cylinders that cause the attrition of inputted materials into smaller particles. Autogenous milling machines can be as small as one meter long by one meter wide by one and a half meters high. Particles from grinding billboard banners and signage could be used in the manufacturing of established plastic products. This moveable milling was seen as a much more efficient, flexible, and sustainable alternative to transporting large unwieldy billboard banners and signage to distant landfill sites. Local autogenous milling is flexible enough to be incorporated into any use cycle of billboards, including when banners are keep in storage for some time in case they are needed for reuse in a further advertising campaign. Moreover, this type of moveable milling is applicable to local recycling of other large unwieldy goods such as truck tarpaulins, etc.

The plastics recycling alliance saw moveable autogenous milling as being an opportunity to better enable production of new types of goods. For example, billboard banners and signage are often made from plastics-coated fabrics. This combination of materials enables billboards to gain the necessary mechanical properties for very large signage, and the necessary surface properties for printing. Autogenous milling can separate constituent materials as separate particles. Thus, fabric particles milled out from billboard signs could be used in the production of composite body panels in highly distributed vehicle production, and particles could be used in the production of plastic components such as wing mirrors for vehicles.

3.3. Analyses

3.3.1. Urban Authority

The urban local authority saw little potential for moveable factories to improve production of existing types of goods, but saw potential for new production in its region by using moveable factories within Web-enabled highly distributed local vehicle production by individuals. This is because it is a viable option, whereas conventional production with large fixed factories was not economically viable. From the perspective of technology diffusion, the urban authority would not be an early proponent of moveable factories to improve existing production, but could be an early proponent of moveable factories to improve new production. From the perspective of industrial psychology, the openness of the urban authority to see the potential of moveable factories for new production suggests a lack of all-encompassing lock-in to fixed industrial production. Similarly, from the perspective of leapfrogging, the urban authority was open to consider new types of production for vehicles with potential to leapfrog fixed industrial production.

3.3.2. Non-Urban Authority

The non-urban local authority saw much potential for moveable factories to improve the production of established agricultural and food goods. They saw these opportunities arising for the potential of moveable factories to make highly distributed local production economically viable. Also, the non-urban local authority saw much potential for moveable factories to enable highly distributed local production of new types of capital goods such as solar arrays. Again, this is because it is an economically viable option, whereas conventional production with large fixed factories was not economically viable. From all three analytical perspectives, the non-urban authority's views were consistent with those to be expected from an organisation finding few advantages from fixed industrial production.

3.3.3. Packaging Company

The packaging company saw limited potential for moveable factories to improve production of existing types of goods, but did see some opportunities for more efficient and more flexible production to enable farms to introduce new types of products. From all three analytical perspectives, the packaging company's views were consistent with those to be expected from an organisation profiting from fixed industrial production. In particular, potential for increased efficiency and flexibility will not be sufficient to bring early adoption of moveable factories as long as fixed industrial factories are a feasible, practical and viable option—even if less efficient and flexible.

3.3.4. Biotech Group

The biotech group saw much potential for moveable factories to contribute to the production of new bio materials to improve existing goods. This was because fixed factories are not a technically feasible option due to the remoteness of the locations for local processing at the beginning of producing some new bio materials. The biotechnology group could see much potential for moveable factories to support flexible artisanal production with natural materials. From all three analytical perspectives, the biotech group's views were consistent with those to be expected from an organisation finding few advantages from fixed industrial production.

3.3.5. Recycling Alliance

The plastics recycling alliance saw much potential to make the local recycling of large billboard signage both operationally practical and economically viable. Thus, local recycling could be combined with local production, for example, of vehicles by end-users. This would reduce the amount of new materials needed to be used in local production. Also, the plastics recycling alliance saw moveable autogenous milling as an efficient and flexible way to provide more recycled materials for components for new types of goods. From all three analytical perspectives, the recycling alliances views were consistent with those to be expected from an organisation finding few advantages from fixed industrial production. However, it is important to note that the recycling alliance comprises companies operating successfully within fixed industrial production for all other aspects of their operations. Thus, their openness to application of moveable production where fixed production is neither practical nor viable suggests a lack of overriding lock-in to fixed industrial production.

3.3.6. Summary

Moveable factories are not a large scale technical system that can sweep across entire economies in waves of technology determinism. Nor are they predesigned technology applications targeted at mass markets, which are subject to individual technology domestications. Rather, moveable factories involve social shaping of technologies by actors who need to think carefully about what manufacturing requirements can be fulfilled by what combinations of technologies at what locations. For example, the biotech group's requirements are very different from those of the recycling alliance. Thus, assessing the potential of moveable factories involves consideration of the effort involved in shifting from the less cognitively and socially demanding option of sticking with fixed industrial factories. Analyses findings are consistent with theoretical perspectives from technology diffusion, industrial psychology, and leapfrogging. In particular, organisations in an industrial economy will consider early adoption of moveable factories for new production if fixed factories are not feasible, practical or viable. In such situations, lack of previous successful use of fixed factories limits the potential for industrial path dependencies and lock-ins acting against moveable factories. A summary is provided in Table 1.

Table 1. Analyses summary.

Participant	Opportunities for Moveable Factory	Fixed Factories
Urban authority	Few, if any, for existing types of good Local vehicle production by individuals	Profitable Not viable
Non-urban authority	Local agricultural goods production Local capital goods production	Not viable Not viable
Packaging company	Few, if any, for existing types of good More efficient and flexible production	Profitable Small value
Biotech group	Biomaterials production at remote locations Artisanal production at remote locations	Not feasible Not feasible
Recycling alliance	Local recycling for existing types of goods Local recycling for new types of goods	Not practical Not viable

Together with research propositions, an analysis framework is shown in Figure 1. Within this framework, adoption timing is influenced by the amount of resistance to shifting away from fixed factories. Shift resistance is influenced by the amount of lock-in etc., and technological complexity, which are mediated by potential rewards from leapfrogging. For example, a company that has long profited from fixed factories (high lock-in) with complex production requirements (high complexity) can have low anticipation of leapfrog rewards. This is especially the case if an organisation holds a monopoly position or is in an oligopoly. Holders of such powerful market positions tend to be leapfrogged rather than introduce leapfrog technologies themselves. Hence, such a company could be less likely to be an early adopter than an organisation with simple production requirements, no successful track record with fixed factories, and anticipation of high leapfrog rewards.

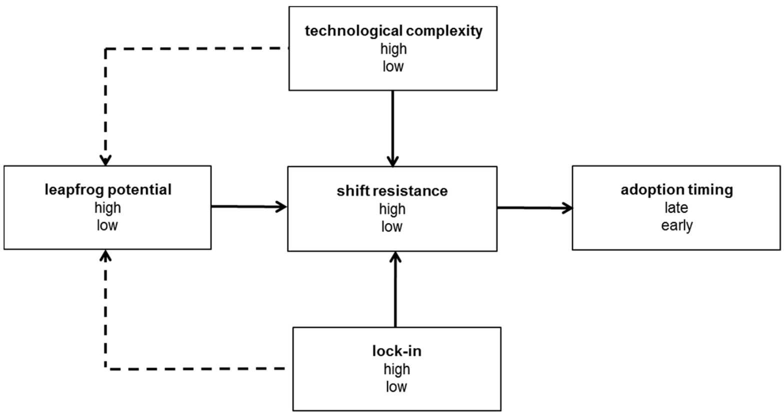

Figure 1. Analysis framework.

Proposition 1. *Established organisations that have complex production requirements and are locked-in to fixed factories will be later adopters of moveable factories.*

Proposition 2. *New organisations that have simple production requirements and have no successful track record with fixed factories will be earlier adopters of moveable factories.*

Proposition 3. *The timing of adoption of moveable factories will be mediated by anticipation of leapfrog effects, which will be lower for established organisations holding powerful market positions than for new organisations seeking to create new markets.*

4. Discussion

4.1. Implications for Manufacturing Technology

Recent decades have seen the bringing together of diverse technological innovations to overcome two important manufacturing trade-offs. First, the quality of goods versus the cost of production [36]. Second, the size of goods versus the sophistication of goods. For example, large expensive cameras and projectors became handheld video camera/players and now are wearable devices [37]. A third trade-off that has been partially overcome is the trade-off between the originality of goods and the efficiency of their production. Hitherto, goods have either been standard and cheap or bespoke and expensive. Although this trade-off persists for one-of-a-kind large capital goods, it is no longer an inevitable trade-off for small bespoke goods such as 3D printed jewelry [38]. Moveable factories can make an important contribution to overcoming a fourth trade-off: the functional sophistication of goods and the localisation of their production. Typically, local manufacturing has involved artisanal skills in making goods of limited functional sophistication. By contrast, the manufacture of goods with sophisticated functionalities has been concentrated in fixed industrial factories. Moveable factories are beginning to enable the in-situ manufacture of sophisticated goods ranging for functional foods to mechatronic assemblies [9]. The range of sophisticated goods that can be manufactured locally can be increased through technology research and development work enabling manufacturing machines to be used successfully away from fixed industrial factories. This can include further reducing the number, size and weight of manufacturing machines, while increasing their robustness during transportation and operation amidst less controlled environments. There are already some examples of radical reductions in the sizes of machine tools: for example, from more than 20 cubic metres (e.g., $3 \times 3 \times 2.5$ m) to less than two cubic metres [39,40]. Important topics include reducing the size and weight of hybrid additive and subtractive machine tools [41] and reducing uncertainty of machine tool calibration [42]. Other opportunities for increasing the range of sophisticated goods that can be manufactured locally with moveable factories may arise from technological advances, such as the Internet of Things (IoT), which can better enable Cyber-Physical Systems (CPS) that entwine digital control systems with physical operations. Currently, research and development efforts are focused upon fixed factories, such as process control systems for large industrial plants. However, IoT and CPS advances can be applied within moveable factories wherever there is robust Internet connectivity [43].

4.2. Implications for Manufacturing Planning

Typical industrial manufacturing planning seeks to find best available balances between factory location, inventory control, and transportation routing. This involves computational simulations of complex mathematical models, for example, including genetic algorithms and particle swarm optimization [44]. Moveable factories can reduce the number of variables that have to be modelled and simulated. In particular, factory location is not a critical variable because factory location is not fixed. At the same time, moveable factories cannot manufacture to stock, because they do not have the storage space to carry stock. Typically, transportation routing models address the problem of designing a set of routes from a central depot to various demand points in order to minimize the total distance covered [45].

An important application for moveable factories in industrial economies can be using them in conjunction with existing fixed factories in order to reduce the disproportionately high costs of "first mile" and "last mile" logistics. These terms are used to refer to initial collection and final delivery transportation that does not achieve economies of scale through bulk handling [46,47]. For example, it has been calculated that the "last mile" of the supply chain contributes 28 percent of the total cost in moving goods [48]. As moveable factories can undertake materials processing and packaging at source of supply, they can increase the efficiency of "first mile" logistics. Also, as moveable factories can be used for efficient manufacturing at point-of-demand, they can increase the efficiency of "last mile" logistics.

In some cases, it may be possible for the whole supply chain to be redesigned so there is no "first mile" or "last mile", as production is carried out fully in-situ with local materials [32]. Thus, the maximum potential for leapfrog effects from moveable factories is realised by going directly between points of supply and points of demand. For example, taking the outputs of billboard recycling directly to downstream plastics manufacturers, taking farm-made dairy products directly to retail outlets, taking beverage products canned at breweries directly to retail outlets, fitting manufactured mechatronic assemblies directly at remote locations, and so on. The dynamics of operating directly between supply and demand make other types of planning models relevant such as those used for the pricing and sale of airline seats. In particular, those who book time for a moveable factory well in advance could do so at a lower price than those who book time at short notice and so cause disruption to what would otherwise be a more optimal sequence of routes [49].

4.3. Implications for Manufacturing Policy

Policy makers' continued fixation with fixed industrial production is paradoxical [3–5]. This is because there are numerous global goals for improving production that can be achieved more easily by leapfrogging over fixed industrial production. First, moveable factories can increase the economic sustainability of manufacturing. This can be done through lower capital costs by not needing to construct physical buildings etc. Also, this can be done by making manufacturing more lean and more agile at the same time [50]. This is possible through the elimination of non-value adding transportation to and from fixed factories, while bringing production to sources of supply or demand exactly when needed. For example, moveable factories can bring increased geographic and temporal precision to agricultural processing and so better support the goals of precision agriculture [51].

Second, reducing the construction of fixed factory buildings and associated infrastructure contributes to more environmentally sustainable manufacturing. Other contributions to reducing the ecological footprint of manufacturing can come from reduced agricultural waste, reduced packaging, and from reduced non-value adding transportation such as that to and from centralized processing plants and large storage depots [52]. Moreover, by reducing fixed capital investment costs and the variable costs of packaging, storage, transportation, etc., moveable factories can contribute to reducing the industrial pressure that drives throwaway consumerism. In particular, the only way to recover the massive financial costs of fixed industrial production is to keep large fixed factories manufacturing continually at close to maximum capacity. This can only be economically viable by continually persuading consumers to buy more goods. This ecologically damaging pattern of escalating consumption to recover the investment costs of production is starting to be addressed by initiatives such as the circular economy. Moveable factories can contribute to such initiatives by reducing financial drivers and by enabling, for example, in-situ remanufacturing that extends the life of existing goods [53].

Third, moveable factories are ideally suited to increasing the distribution of manufacturing, which can contribute to manufacturing being more socially sustainable [54]. Fourth, moveable factories can better meet the goals of resilient production: robustness and adaptability [55]. This is because, compared to fixed factories, moveable factories are far less vulnerable to climate and conflict events and are far more responsive to market changes because moveable factories can be driven away from events that would negatively affect fixed factories and driven towards new supply or demand. Thus, moveable factories can contribute to more resilient sustainable manufacturing. This is important for many industrial economies where industrial production is concentrated in only a few regions. In several European countries, for example, industrial production is concentrated in the northern regions, which leaves persistent poverty in southern regions [56]. Bringing fixed industrial infrastructure would require massive capital investments over long periods of time. By contrast, moveable factories can be brought to southern regions much more quickly and at much lower capital costs.

4.4. Limitations and Future Work

This study has considered one industrial country. Previous studies have considered countries that have not industrialised [6,7]. Future work could be carried out in middle-income, partially industrialised countries and in additional industrialised and non-industrialised countries. Findings from field studies concerned with moveable factories can be compared and contrasted with conceptual papers that contain argumentation for smaller (mini) factories but have not encompassed the potential of moveable factories [10]. It can be argued that previous research, this research, and future research about moveable factories is action research. This is because it brings about change from participants not being aware of moveable factories to them being informed about moveable factories. Hence, it is important to state explicitly the limitations of moveable factories when introducing information to participants.

5. Conclusions

The state-of-the-art in moveable factories has been described. The potential for uptake of moveable factories in an industrialised economy has been investigated through interviews with a range of different types of organisations. Study findings are consistent with theoretical perspectives from technology diffusion, industrial psychology, and leapfrogging. In particular, study findings indicate that organisations in an industrial economy will consider moveable factories for new production if fixed factories are not feasible, practical, or viable. The potential for moveable factories to offer increased efficiency and flexibility may not be sufficient to motivate a shift from fixed factories. Nonetheless, increased consideration of moveable factories during the research and development of manufacturing technologies can further reduce the trade-off between the functional sophistication of goods and the localisation of their production. This, in turn, can provide impetus for policy makers to go beyond their fixation with fixed industrial production.

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