

INTRODUCING THE CONCEPT OF HYPERCONNECTED MOBILE PRODUCTION

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Abstract

Many globalized businesses are trying to cope with growing competition by strategically expanding their dedicated network of production facilities so as to be able to offer and to deliver time and price competitive offers to their clients across the world. In this paper, exploiting Physical Internet principles, we introduce the concept of hyperconnected mobile production that can alternatively enable businesses to dynamically expand and contract as necessary their production capacity in regions worldwide. First, hyperconnected mobile production exploits open fabs from multiple parties readily available in those regions. Second, these fabs are to rely on plug-and-play production modules. These modules are to be flowed in and out of open fabs worldwide by the fab operators or their business clients so as to absorb dynamic production requirements from customers. Third, the production modules are to be dynamically re-configurable through adding and removing plug-and-play modular resources. We first show that hyperconnected mobile production builds on eight innovation threads: distributed, outsourced, on-demand, modular, additive, mobile, containerized and hyperconnected production. We then provide an overall description of key facets of the hyperconnected mobile production concept and finally elicit a number of promising research avenues.

Keywords: Hyperconnected Mobile Production; Physical Internet; Distributed Manufacturing; Outsourcing; Modular Production; On-Demand Manufacturing; Modular Production; Containerized Production; Agility; Efficiency; Sustainability.

1. Introduction

To thrive in a competitive world, businesses are striving to offer high-quality products and deliver them to their worldwide customers faster and cheaper. Three key complementary strategies are used by businesses to tackle this challenge: fast delivery to customers, near-to-customers inventory deployment and distributed near-to-customers production. In this paper we focus on the third strategy: contributing to making on-demand near-to-customers production efficient and profitable.

We aim to contribute to avoiding having to pay high charges to ship goods fast from far away to fulfill customer orders or having to produce for stock and to deploy inventory across the world so as to mitigate fast delivery costs. Exploiting Physical Internet principles, we introduce the concept of hyperconnected mobile on-demand production that can alternatively enable businesses to dynamically expand and contract as necessary their production capacity in regions worldwide.

We have structured the paper as follows. First, we describe the threads leading to the introduction of hyperconnected mobile production. Then we describe the essence of the concept. We proceed to map the set of actors, emphasizing the roles, options and decisions of key actors. Finally, we highlight research and innovation avenues.

2. Threads leading to hyperconnected mobile production

As depicted in Figure 1, we identify eight key threads that merge to open a new era of hyperconnected mobile production that may completely transform the manufacturing playing ground: (1) distributed production, (2) outsourced production, (3) on-demand production, (4) modular production, (5) additive production, (6) mobile production, (7) containerized production and (8) hyperconnected production.

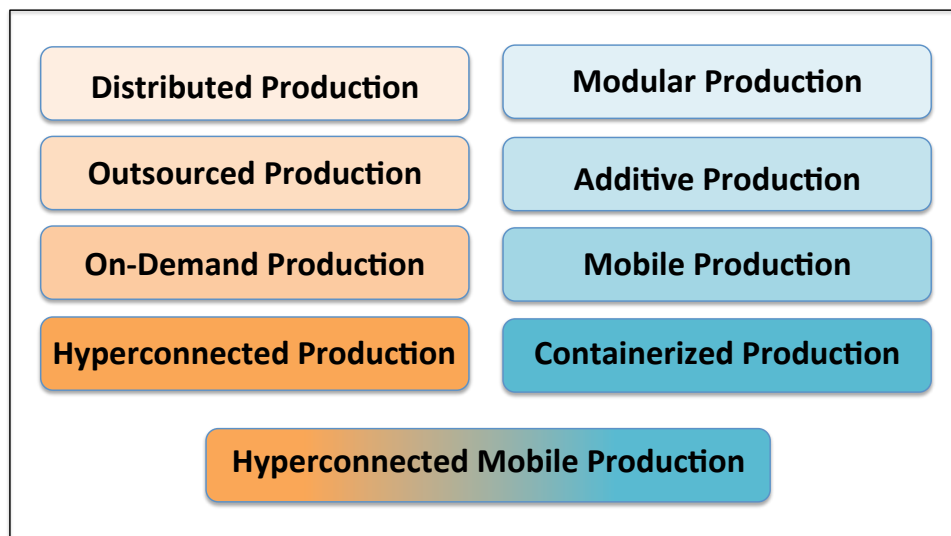


Figure 1. Key Threads Leading to Hyperconnected Mobile Production

The first thread is distributed production. Multinationals have long learned to deploy factories in various markets across the world. Yet the time pressure is getting much tougher, with significantly shrinking lead times expected by customers. This induces companies to consider networks of smaller factories nearer to localized markets. The key problems lie on one side in losing economy of scale when shifting from large to small factories, and on the other side in freezing capacity in small factories across localized markets to sustain peak times, thus leading to extra capacity requirements.

The second thread is outsourced production. Focused subcontracting and wider-scope outsourcing have long been used by businesses to get access to localized production capabilities and capacities. When production processes are relatively easy and generic, with a large number of production service customers, then this avenue has proven transformative. For example, this is the case in electronic circuit board assembly and in electronic consumer goods assembly. It has also proven highly efficient when production processes are very complex and costly, hard for each business to justify, as is the case in semiconductor fab assembly. In the above cases, many brand companies do not touch their products, rather relying on the capabilities and capacities of a network of production fabs, contracted ad hoc or strategic partners.

Subcontracting and outsourcing production becomes tougher when the production processes are felt by businesses to be a competitive advantage, to be different from others and to require distinctive production facility configurations and technologies. It is also tougher when production processes are monolithic, requiring extensive tightly integrated factories. This phenomenon is one of the top reasons why so much of production is still limited to internal often-large factories.

The third thread, on-demand production, extends on the second thread. Rooted in production-to-order and just-in-time production, as well as on personalized production, mass customization and postponement, it exploits scalable and adjustable assembly and manufacturing processes work to complete customized packages based on real-time or current data from a client [1]. It is achieved using cloud-based software platforms that make it easy for businesses to get instant quotes for production, manage projects, and track inventory from any browser, anytime (e.g. [2]).

As a fourth thread, modular production has long been conceptualized as offering huge potential in terms of adaptability, agility and flexibility ([3], [4]). The idea is on one side to break down the monolithic highly integrated production processes into a set of production modules that can be interconnected as necessary so as to collectively perform the overall required processes, and on the other side to design the facilities as an easy-to-reconfigure set of modular spaces and facility services [5].

The fifth thread, additive production (manufacturing) is a vivid example representative of years to come. It is about printing products on demand from a single 3D printer that may be located anywhere as long as there is capability to transfer the digital model of the product, to have an adequate available printer and to have the right printing

material available. Additive production can be seen as enabling on a wide scale single-machine production modules, making the product in a single step, as is the case with an injection-moulding machine for simple products. Basic 3D printers are already available below 1,000\$, making them home affordable, while the price, quality and speed of professional printers are improving at a fast pace, leading so many companies to experiment with them and to fill niche requirements. As such technologies mature, the mere notion of manufacturing products in large remote factories may well become obsolete in several industries.

As a sixth thread, mobile production has long been used in industries with geographically dispersed demand for production capacity over short periods. Mobile production units are generally implemented within a trailer or carried in a trailer. They are offered to production-demanding clients for use during their short peak season. Small wine producers commonly use mobile wine bottling units in peak periods. Similarly, mobile chipping units are also common in the wood industry, and mobile butchery units in the cattle industry. Examples abound, getting more respected as viable alternatives with advances in technology and maturity of the mobile producer businesses.

The seventh thread, containerized production, combining features from the modular and mobile production threads. It uses containerized production units to offer plug-and-play modularity and mobility capabilities. Leading companies such as Procter & Gamble and Bayer recently demonstrated their experimentations with containerized modular production ([6], [7], [8], [9]).

Procter and Gamble has investigated the utilization of containerized labs which are designed to be quickly installed, started up and relocated, enabling operations in targeted sites to grow or to shrink with demand by adding or removing lab modules [7]. They have worked with Farber and Germfree towards designing mobile laboratories conceived as production modules having small footprint and requiring low investment, as shown in Figure 1 (Source: [9]).

Exploiting research performed in the European F³ Factory project (www.f3factory.com), Bayer has started experimenting the shift from a multi-step synthetic batch process for pharmaceutical intermediates to a fully continuous process in a modular, flexible infrastructure – including downstream processing [6]. Figure 2 shows Bayer's container-based process production module in two contexts: producing in a factory and being loaded on a vehicle for inter-factory transfer. Bayer's implementation reveals a modular, continuous production technology using novel equipment and processes in a standardized, container-based manufacturing environment for low to medium scale production in the chemical industry.



Figure 1. Modular P&G approach where a facility grows from two to three modules
(Source: [9])

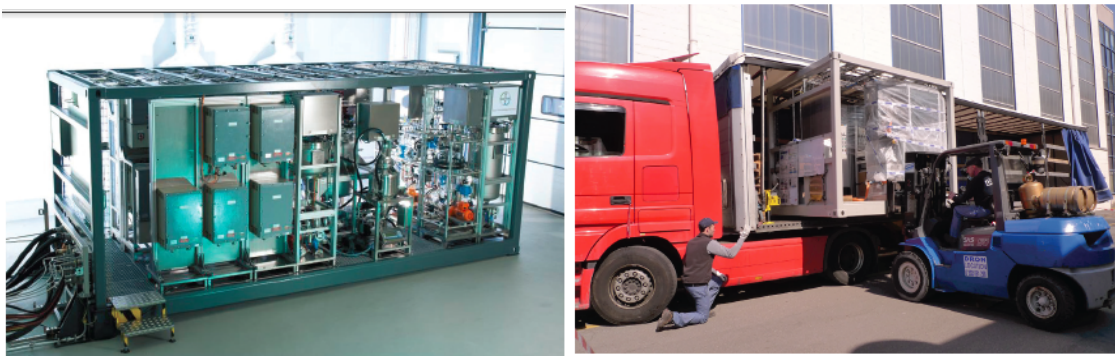


Figure 2. Bayer's process equipment container in plant and in transit
(Source: [6])

The final eighth thread, hyperconnected production, stems from the introduction of the Physical Internet (PI) ([10], [11], [12]) that aims to improve by an order of magnitude the economic, environmental and societal efficiency and sustainability of the way physical objects are moved, deployed, realized, supplied, designed and used around the world. PI is a global hyperconnected logistics system enabling massively open asset sharing and flow consolidation across numerous parties and modes through standardized encapsulation, modularization, protocols and interfaces [13]. Hyperconnectivity is achieved through physical, digital, operational, transactional, legal and personal interconnectivity, ultimately anywhere anytime. PI aims to broadly transform supply chains and logistics. Three facets pertinent to this paper are synthesized below.

First, it aims to enable hyperconnected transportation [14] that moves goods, encapsulated in modular packaging, handling and transport containers, from their source to their destination through relay-based routing from open hub to open hub. It offers complete visibility on the location and state of the containers, notably through Internet-of-Things technologies. Flow is consolidated across multiple parties at each certified hub, getting containers heading in the same direction to be loaded together in a timely way in

the most appropriate vehicles from certified providers exploiting the most pertinent mode of transportation.

Second, PI aims to enable hyperconnected distribution [14] to dynamically deploy goods, encapsulated in modular containers, across a web of open certified logistics centers so as to be readily positioned near points-of-demand for enabling fast order delivery and/or pickup. In a cloud storage spirit, hyperconnected distribution protects the confidentiality of the container-encapsulated goods yet provides as-needed visibility on container location and state. Open facilities may encompass the likes of warehouses, mixing centers, distribution centers, fulfillment centers and smart lockers, offering their space openly to multiple parties.

Third, most pertinent to this paper, it aims to enable hyperconnected production [14] so as to realize products on demand through a web of open certified production facilities (here nicknamed open fabs), supplying these open fabs and shipping from them in modular containers using hyperconnected transportation. Realizing products encompasses combinations of manufacturing, assembling, finishing, personalizing, packaging, refurbishing, etc., as pertinent. Hyperconnected production extends outsourced and on-demand production capabilities of threads 2 and 3. Open fabs can be stand-alone factories such as semiconductor fabs and contract electronics assembly plants. They can also be embedded in logistics facilities, for example completing the personalization of ordered products according to a postponement strategy.

Overall, interlacing the distributed, outsourced, on-demand, modular, additive, mobile, containerized and hyperconnected production threads leads to a vision that is here termed hyperconnected mobile production. The reasoning for using only the hyperconnected and mobile features in the vision expression is as follows. The additive feature is contributing to this vision by simplifying the production processes, making them ultimately single-step and easy to distribute. The modularity and containerization features are core to the Physical Internet and thus merged into the notion of hyperconnectivity. Finally, the on-demand feature is strategically inducing the notion of mobility, moving production capacity where needed to readily serve localized demand.

3. The essence of hyperconnected mobile production

Hyperconnected mobile production aims to allow businesses to efficiently expand and contract dynamically as necessary their production capacity in regions worldwide. It exploits combination of business-dedicated and open fabs readily available in those regions, such fabs relying on plug-and-play production modules and resources so as to absorb dynamic production requirements from their customers. The modules embed their core production capabilities and are designed to be configurable with plug-and-play resources enabling specific production capabilities beyond the module's core capability set. Production modules and resources flow in and out of fabs worldwide according to the overall demand dynamics. Businesses wanting their products made in specific fabs, yet

requiring specialized processes, may orchestrate getting the right production modules in the targeted fabs and the right resources to enable them to make process the products.

It exploits the hyperconnectivity induced by the Physical Internet to insure efficiency of moving containerized production modules and resources from their current location to their targeted location, such locations being fabs or logistics facilities (such as warehouses and distribution centers), either open facilities or facilities dedicated to the business and its partners. In the hyperconnectivity spirit, the production modules and resources can be owned by the business having products to be made, by the open fabs offering production services, or yet by third parties specialized in providing such modules and resources either in specific regions or across the world.

Consider as an example the following simple case of a company needing production of its two products A and B. Both products require the same four process steps P.1 to P.4. If one assumes the company to be in the knock-down wood furniture industry, these steps could correspond to cutting pieces of wood (P.1), drilling holes in wood parts (P.2), putting a finishing coat on the parts (P.3) and packing wooden parts and hardware in a box for shipping (P.4). Figure 3 illustrates three potential fabs that may be alternative production service providers to the case company.

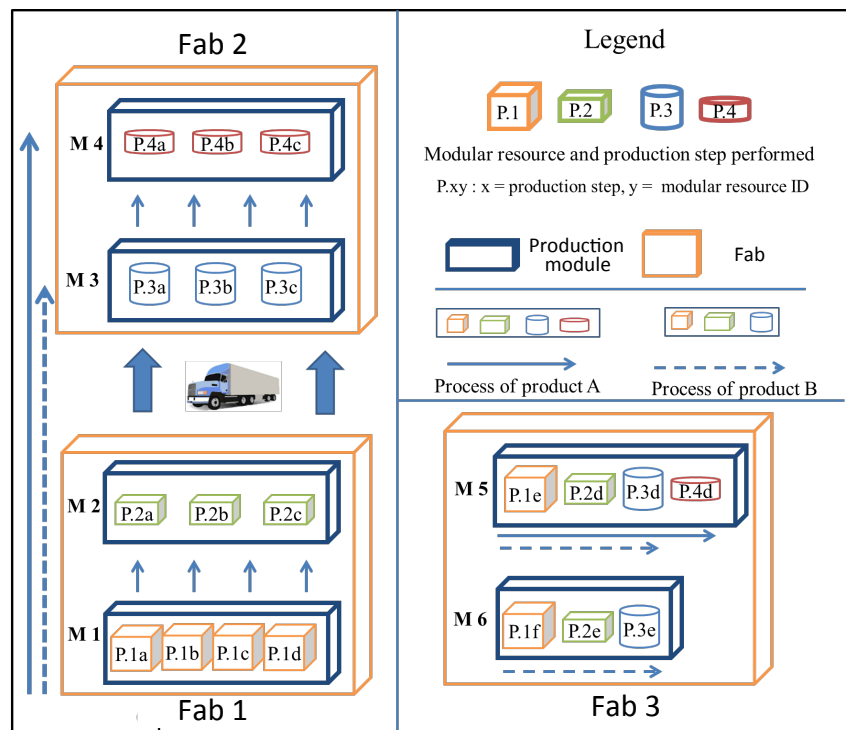


Figure 3. Simple examples of fabs, production modules and modular resources

Fabs 1 and 2 currently embed production modules that are function-oriented (single-process) [15]. Fab 1 has two production modules focused respectively on process steps 1 and 2, while the two production modules of fab 2 are focused on steps 3 and 4 respectively. Each production module in both fabs is currently configured through using modular single-process resources. The case company may use the services of such fabs when it needs production capacity for specific process steps in given regions, such as near materials sources for fab 1 or near clients for fab 2. Fab 3 alternatively provides process-oriented production modules capable of including distinct modular resources enabling them to perform several process steps. Relative to the case company, production module M5 is configured to perform all the required steps for products A and B while module M6 is configured to perform all the required steps for product B and the three first steps of product A. The company may have its products A and B entirely made in fabs such as fab 3 on a module such as M5, or yet get them ready to be finished in a module as M5 and then shift them to M6 for completion or yet have them transported to a fab such as fab 2 for having its final step 4 completed.

The network exploited by the case company is dynamically evolving through time to match distributed demand requirements. Figure 4 illustrates a potential state at some specific period. It depicts the key demand zones for its products, as well as their relative demand levels, across the U.S.A. territory. The company currently relies on six open fabs with available modules M3 and M4 (from Figure 3) to complete production of its products near markets, from semi-finished products made in two open fabs with modules M1 and M4. These two fabs are also used to make entire products A and B for nearby markets using modules M5. It also relies on two open warehouses to store its modules and resources not currently used in fabs, when it is more efficient than letting them in the last fab they were used or the next they are to be used. As necessary, the company may use open distribution centers to store products made in anticipation of demand. Figure 4 also illustrates two products C and D from other businesses in order to emphasize the open sharing perspective, as these are also competing for the production services of the fabs.

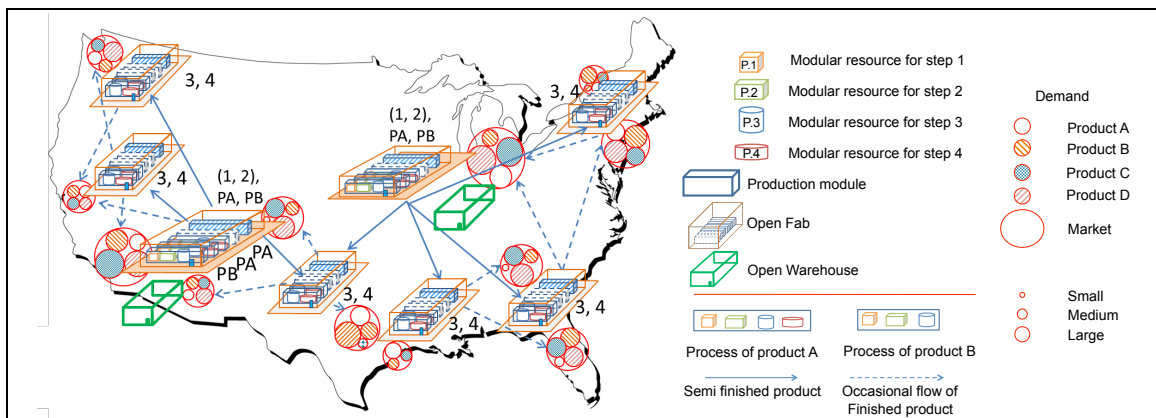


Figure 4. Punctual state of a hyperconnected mobile production network

Whereas Figure 4 focuses on depicting a specific state in some period, Figure 5 alternatively emphasizes the inter-period dynamics of module and resource deployment in hyperconnected mobile production. It uses our simple company case exploiting mobility of resources and modules across open fabs and warehouses. The logic is that by exploiting such mobility when available at a lower cost than acquiring further resources or modules, it opens opportunities for achieving high level of production and flow efficiency even if distributed demand changes constantly, by relocating resources and modules as needed.

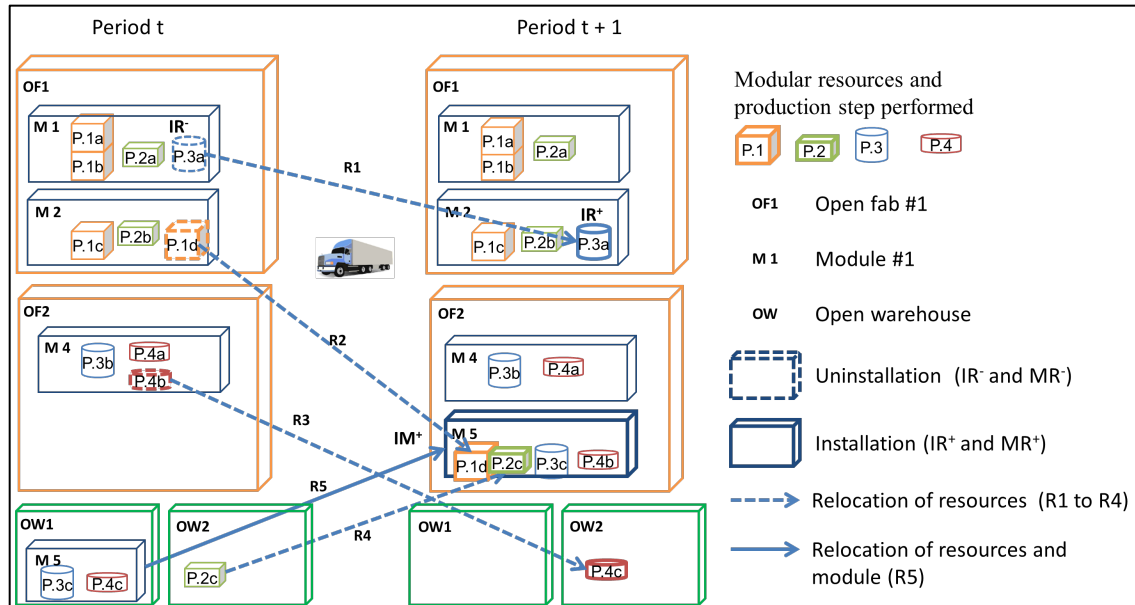


Figure 5. Illustrating the module and resource deployment dynamics in the context of hyperconnected mobile production

Specifically, Figure 5 illustrates the following types of moves:

- A. Relocation of a resource r from a module m of a fab in location l to:
 - 1) Another module m' in the same open fab
 - e.g. R1 resource P.3a in M1/OF1 moved to M2/OF1;
 - 2) Another module m' of another open fab l'
 - e.g. R2 resource P.1d in M2/OF1 moved to M5/OF2;
 - 3) An open warehouse at location l'
 - e.g. R3 resource P.4b in M4/OF2 moved to OW2;
- B. Relocation of a resource r from a warehouse l to module m' of an open fab in location l'
 - e.g. R4 resource P.2c in OW2 moved to M5/OF2;
- C. Relocation of a module m of the open fab or the open warehouse in location l to another open fab or to an open warehouse, in location l'
 - e.g. R5 module M5 in OW1 moved to OF2.

Such relocations involve a number of activities that induce costs to be balanced with the expected savings. These include deactivating, uninstalling, transporting, storing, installing and activating modules as well as resources within modules.

4. Key actors in hyperconnected mobile production

In hyperconnected mobile production, we distinguish six key types of actors:

1. *Users*: Businesses having products to be made/processed so as to serve their client needs;
2. *Production Service Providers*: Businesses offering their services for realizing production on behalf of users, expected to have adequate capability and capacity to fulfill their offers;
3. *Module and Resource Providers*: Businesses offering as a service the dynamic availability of modules and resources to users or production service providers;
4. *Module and Resource Suppliers*: Businesses offering modules and resources for purchase or lease to users, production service providers as well as module and resource providers;
5. *Logistics Service Providers*: Businesses offering logistics services to the above four types of actors to transport and store goods, modules and resources;
6. *Digital Platform Providers*: Businesses offering platforms and applications, either through licensing or as a service, sustaining the collective activity of the above five types of actors.

Actors from each of these types may be stand-alone businesses or units of larger businesses. For example, a specific user may have an internal unit acting as a production service provider that can be complemented by exploiting external open production service providers anywhere across the world.

Fabs are the main types of facilities, corresponding to any facility that can be considered for potential production, such as factories, plants and production zones within logistics centers. Such facilities are typically owned and/or operated by production service providers. The fabs are said to be open fabs when their production service provider makes them dynamically available on the public market to any user. Such open fabs may be available for very short jobs as well as for longer-term contracts. Fabs may alternatively be dedicated to a single user or to a set of collaborative partners.

Fabs may or not be modular, designed to host production modules and resources, in as much a plug-and-play mode as possible. Operators of modular fabs have the following options regarding the modules and resources necessary to meet the demands of users requiring production services:

1. Acquiring them through purchasing or long-term leasing from a module/resource supplier;
2. Appropriating them for a specific duration from a pool shared with partners or from an open pool operated by a module/resource provider;
3. Allowing client users to provide them.

Users are also exploiting options 1 and 2 to manage their dedicated sets of modules and resources.

For a user perspective, fabs are said to be capable when the user does not have to get involved in providing them modules and/or resources to insure that they have sufficient internal capability and capacity to meet their production service demands. Such capable fabs may or nor be modular fabs. In increasing degrees of freedom, hyperconnected mobile production enables the following decision options for a user to have operations on its products made:

1. Having them done steadily in a set of capable fabs;
2. Shifting production assignments dynamically to capable fabs;
3. Shifting production assignments and modules dynamically to modular fabs;
4. Shifting production assignments, modules and/or resources to modular fabs.

In order to support and enhance decisions relative to the above options, both production service providers and users may thus have to manage their sets of modules by dynamically:

1. Acquiring, appropriating or letting go of modules and/or resources;
2. Moving modules and/or resources to another fab or warehouse;
3. Storing modules and resources in a fab or a warehouse;
4. Reconfiguring modules, altering their capability and capacity through the fast and efficient near-plug-and-play removal and installation of resources;
5. Planning process steps performed by a module and its resources so as to realize operations on a specific set of products;

When making their decisions in the context of (1) geographically dispersed clients demanding fast response to their stochastic and variable demands and/or high availability of their demanded products, (2) the existence of a wide web of geographically dispersed service providers with their fabs, modules and resources, users are notably balancing several objectives:

1. Maximizing profitability from generated revenues minus induced supply, production and logistics costs;
2. Maximizing service capability and performance;
3. Minimizing their set of engaged assets;
4. Maximizing utilization of their engaged assets;
5. Maximizing their distinctive product and production capabilities and offerings;
6. Minimizing induced environmental footprint;
7. Maximizing their resilience to disruptions.

As exemplified by the user example above, hyperconnected mobile production adds degrees of freedom in decision making and increases potential performance, yet it requires to reshape the decision making framework of all actors in the ecosystem so as to exploit smartly the upgraded set of options.

5. Conclusion

In this paper we have introduced the concept of hyperconnected mobile production. It is about enabling smart, agile pro-activeness in dealing efficiently and sustainably with high-variability market demand through dynamic contracting of production to fabs, providing them with movable plug-and-play production modules that may be reconfigurable using movable plug-&-play resources. The concept builds on the game-changing convergence of eight threads: distributed, outsourced, on-demand, modular, additive, mobile, containerized and hyperconnected production..

We have described the essence of what hyperconnected mobile production and illustrated how it is to operate, emphasizing the new degrees of freedom and decision-making options for the various actors. Much research and innovation remains to be done to evolve from the presented high-level vision to make it a reality exploited in large scale by businesses around the world. We hereafter provide five key threads for further research and innovation. Indeed there is a need to:

1. Expand the early research and innovation in containerized production to emphasize the plug-and-play capability and standardized encapsulation of containerized production modules, to include modular reconfiguration capabilities through plus-and-play resources, and to develop the enabling transport, handling and storage technologies. These building blocks are key to hyperconnected mobile production, which should be designed and engineered in an open system perspective, in line with Physical Internet principles.
2. Rigorous potential assessment studies through systematic modeling and simulation of large-scale exploitation of hyperconnected mobile production by major actors such as original equipment manufacturers or top brands in the consumer goods, pharmaceutical and food industries; and across entire such industries. The assessment should encompass on one side the perspective of the individual actors and on the other side the perspective of the entire ecosystem.
3. Formalize the key decision processes for each type of actor in hyperconnected mobile production, developing optimization models and solution engines capable of supporting such decision making at the size and pace required by industry. We have made early efforts in such a direction for supporting decision-making by users assuming non-reconfigurable production modules through the introduction a formal mathematical model in a production-to-order context (Marcotte et al. [16]).
4. Develop the digital and transactional platforms capable of sustaining hyperconnected mobile production on a large scale, dynamically interconnecting numerous actors across the ecosystem. This should lead to smart seamless standardized information exchange, interfaces and protocols.
5. Perform pilot tests in industry to validate the potentialities and most important to uncover all the hidden hurdles and enablers otherwise hardly perceivable, leading to rounds of further research and innovation. There should be rounds of such pilots, starting with humble highly focused trials to more comprehensive wide-spread tests, and eventually to growing adoption by industry.

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