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Proposal for a procedure to design multipurpose urban factories

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Abstract

European industrial production has been centralised in large installations located far from the places of consumption. This relocation can be explained by the search for economies of scale and the avoidance of nuisance associated with certain activities, at a time when the clean technologies that exist today were not available. It has also led to a hyper-specialisation of factories, with the need for large volumes of the same category of products in a given location. Researches exist about the identification of possible urban plant locations and their potential negative and positive impacts according to multicriteria models based on quantitative or qualitative data. Although they focus on installations producing only one type of product, it may be possible to develop multipurpose urban production sites that would be capable of designing and manufacturing a multitude of different products able to satisfy a range of needs, while sourcing within an optimised perimeter and strengthening the local resilience. This article presents a methodological proposal that could help develop a model of multipurpose urban factory based on identification of a need, definition of the products which can fulfill the need, and the means to manufacture them. After a literature review and the description of the method, a case study about hygiene products is presented. Then, an environmental screening is used to verify the relevance of the approach. Finally, the method and the case study are discussed, and perspective of further research are proposed.

Keywords: Urban factory; LCA; Material selection; Factory design

1. Introduction

Urban factories are installations implemented in urban zones whose main goal is to reduce the separation between consumption place and production place, the life place and the workplace. This idea is consistent with the fact that more than half of the world's population currently lives in cities [1]. Urban factories seem to be a promising solution to prevent commuting or other pollutant activities related to globalised supply chains. However, they cannot be effective without considering local consumption patterns and a strong definition of sustainability.

The key steps of urban factories are (1) urban mining and raw material extraction, (2) prefabrication, (3) assembling, (4) distribution and (5) end of life [2]. All these stages must be considered to assess the entire life cycle of the product and to find the more sustainable way to manufacture them.

The main goal of this study is to propose a scenario in which an urban factory would be implemented in Grenoble considering the ecosystem of this city. This infrastructure will meet some strict constraints due to its implementation in urban zones, including noise attenuation, CO_2 emissions, waste stream management, surrounding ecosystem sensitivity or water cycle. To reach such goals, some current processes have to be improved. For instance, reducing the uncertainty margin when calculating would enable the urban factory to spare material by foresee the needed quantities of raw materials precisely. Moreover, fabrication process with a better environmental impact (less energy, water, or material need) should be preferred as for instance additive manufacturing (fewer losses).

The urban factories are mainly designed to meet the need for sustainable development. Juraschek et al. [3], have detailed the Sustainable Development Goals (SDGs) defined in United Nations [4] that urban factories can help to reach. The main potential contributions of urban industries are essentially the promotion of economic growth and so the increase of GDP (Gross Domestic Product). Urban factories would enable to have better work condition (e.g. no commuting) and imply a cleaner industry. In addition, its advantages include improved energy management with a more secure and sustainable production, cleaner end-of-life of products (e.g. urban mining). The circulation factories concept is applied though manufacturing, remanufacturing, and recycling [3]. Thus, urban factories can meet environmental (decreasing emissions), social (employment) and economic (value creation) goals.

2. Methodology

An urban factory requires resources to manufacture products. These resources are defined as "*means for performing an action or executing a task. It can be a tangible or intangible good. Every resource is bound to time and capital*" [5]. Among these resources, this study will strongly focus on materials that are intrinsically linked with two other resources: knowledge and energy.

Fig. 1 summarizes the methodology used in this study. First, the target market is defined. The aim is to produce manufactured products that are necessities but still have a sufficient added value. Thus, the need to be met will be chosen, and products that meet this need will be investigated. Then, the main constraints of the urban factory will be highlighted. This would enable us to define a list of products that are possible to manufacture in the chosen territory and that meet our requirements. After that, suitable materials will be characterized by their properties and their environmental impacts. Once we know how the products are going to be made, the production chain must be designed. At this stage, our scenario of urban industry is completely defined and environmental impact assessment through Life Cycle Assessment (LCA) can be done. The main goal of this LCA is to compare the impacts of a classical industry and the urban factory designed in this study. Finally, an economic and ethical assessment will be done to ensure that this idea is feasible.

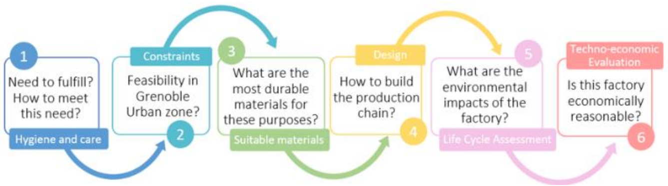

Fig. 1. Method to construct the urban factory.

3. Case study: hygiene products

This case study aims to apply the method detailed in Fig.1 to a concrete place. The goal of this part is to investigate more deeply the steps of this method.

3.1. Step 1: Choice of product category

To narrow the search, hygiene and care products are focused on because they seem to be essential products in the daily life of an average French person. In this category, different needs must be identified such as brushing one's teeth, washing one's body, blowing one's nose, shaving, cleaning one's ears, removing make-up, and cutting one's nails. Based on the needs identified, the products that can meet these requirements have been listed.

3.2. Step 2: Constraints related to the local context

Due to the location of the industry, constraints will push us to choose the products that the urban industry of the scenario will fabricate. Two orders of constraints were distinguished: constraint related to the position in Grenoble (supplying of raw materials with the surrounding suppliers and resources), and the implantation inside an urban zone (space occupancy, no emissions, no noise). These two constraints are connected to material choice [6].

As the scenario is focused on Grenoble, it is essential to investigate the main sources of raw materials surrounding the city, with an extending radius where no close supplies could be found. Thanks to the examination of national statistical geographical institute [7], eight species of wood cultivated in the Rhône-Alpes region were chosen: Oak, Beech, Ash, Chestnut, Douglas, Pine, Spruce, and Fir. Regarding fibres, it seemed complicated to find a sufficient fibre production volume in France and even in Europe. Nettles, flax and hemp are the main fibres produced in France. Cotton is the most used textile fibre and is often imported from India. Polymers and metals can be easily found in Europe.

Being in an urban zone limits the possibility to resort to polluting means of transportation. In this example, some products were removed from the list because of the need for heavy industry in their production, the resulting noise, and the need for a big water source for production. For instance, the production of paper seemed difficult to set up in the urban zone, so we considered that paper toilet, paper towel, and disposable tissue are not practicable to produce in our scenario, and remained produced is large factories outside of cities.

3.3. Step 3: Suitable materials

Material properties and environmental impacts were studied to select the most suitable materials for each product. To do so, the software CES Edupack was used [8]. This comprehensive software is used to compare material properties, to design processes and to do eco-audits. Eco-audits are comparison between two or more products regarding CO2 emissions, energy needed, and cost induced by production or use. The focus will be on the material properties such as Young's modulus, recyclability, water use and energy needed for the elaboration [9]. The databases used are Eco design level 3 and Material sciences and engineering database.

The different properties of the studied woods did not enable to disqualify a material from the study. Oak is the heaviest, stiffest, and the most expensive wood. Bamboo needs higher energy to be produced. Beech, Ash, Spruce, Fir, Douglas, and Pine have good and suitable properties for toothbrush handles for example and a better environmental impact than bamboo.

Textiles pose a certain number of conditions to be within the framework of sustainability. Indeed, producers in certain countries do not always comply with labour rights and environmental regulations [10]. The use of chemical substances to obtain the final product also raises some issues in wastewater treatments, air pollution and health. In addition, the CES database does not contain any information about nettle, abaca, mohair, angora, recycled polyester, biologic cotton, bamboo or soya fibres. However, nettle should not be forgotten as it represents a promising fibre in France. There is also emerging technologies for textile using food waste, microbes, fungi which could be alternatives in the near future [11].

Vegetal fibres appeared to be the best alternatives with this project in regard to environmental and resistance purposes. They need lower embodied energy for primary production, and they are showed cheaper than artificial fibres in CES, except for silk. Each plant has some advantages. For instance, flax has high productivity with little fertilizer; hemp, with mechanical properties similar to flax, absorbs more CO_2. For sportswear, polyester is still interesting. In this case, it would be better to use these 100% polyester clothing to be able to recycle them. Cotton crops need a lot of water and chemical treatments, except if it is organic. Unfortunately, organic cotton is not listed in CES and it was not possible to create it, considering yield differences in this project.

As a toothbrush could be manufactured in wood instead of polymer, CES compared the impact of wood and polymers to help decide. Wood was the material of choice for a bathmat or a toothbrush. The polymer was the material of choice for the toothbrush hairs. Polymers or wood have been studied both to perform the following functions: toothbrush handle and head, shaver handle and head, oriculi, clothes peg, hanger, cotton bud. In order of preference, the material will be ranked as follows: (1) Pine, beech, ash, because they have a very low footprint on the environment and acceptable mechanical properties, (2) oak and bamboo have very good mechanical properties but a sensible higher impact on environment than other woods, (3) PLA (Polylactic acid) and PP (Polypropylene) have the lowest embodied energy in polymer class, a reduced need in water and good mechanical properties, (4) PA6 (Polyamide 66) has a higher embodied energy and need in water, a high CO_2 footprint but has good mechanical properties.

Eco-audits have been investigated in CES to analyse the environmental impacts of a scenario. This tool helped to imagine different scenarios and to choose those which reduce CO_2 emissions, energy consumption, and costs. For each object, the method is the following: (1) to choose the material that will be used in different scenarios, (2) to define the dimension of each part of the product, (3) to calculate the needed mass of each material with their densities, (4) to enter the components data on CES (quantities, material, recycled percentage, mass, primary and secondary process and end of life), (5) to fill in the requested assembly, finishing touches and transport information, (6) to detail the use of the product (time of life, country of use, if it is mobile or static, the energy needed…). After entering all this information, the software draws up a balance sheet with a graph for each indicator: energy, CO_2 footprint, and cost.

PA6 cast, PP copolymer 40% long glass fibre, PLA general-purpose, bamboo and beech were chosen for comparison for the head and the handle of the toothbrush. The scenario supposed the realisation of one toothbrush whose handle is 14cm long, 1cm wide and 0.6cm thick. The toothbrush head is detached from the handle for reuse. There are about 1,400 nylon bristles (PA6) on the head with a diameter of 0.3mm and a length of 1cm. For polymer, the primary process chosen was casting and the secondary process selected was cutting and cropping. For woods, the primary process is predefined on CES and the secondary is cutting and cropping. Zero recycled content and end-of-life landfill were selected to achieve the worst-case result. Fig. 2 shows the energy and CO_2 results.

Woods are more economical both in terms of energy, CO_2 footprint, and costs. The cost of the polymers is approximately the same whichever is selected, it depends on most of the primary process: casting. The different PA6 polymers had a higher impact. The choice that we could make would keep PA6 only for the bristles of the toothbrush because it seems to be the most suitable material. For the handle, and the head we would prefer beech wood. A model could also be proposed in PLA, which has lesser impacts in the polymer class. However, its impacts are more than 3 times those of beech wood. As the clothe peg, clothes hanger, oriculi, and razors are simple objects with a main part that can be either plastic or wood, the study was similar to that of the toothbrush.

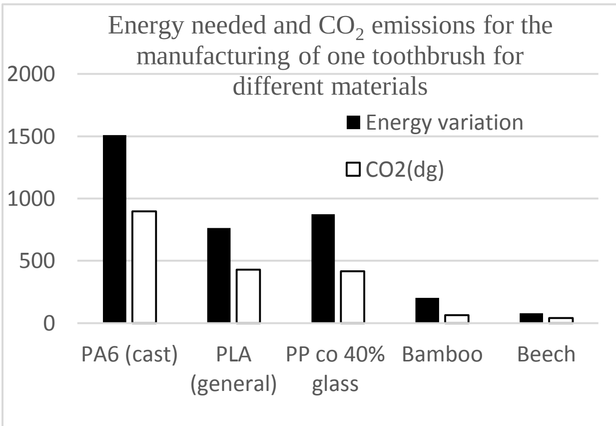

Fig. 2. Energy needed and CO2 emissions for the manufacturing of a toothbrush.

Metals for the razor blade, the spring of the cloth peg, and the hanger hook have been investigated on CES. The most suitable material seems to be stainless steel and its impact is quite the same as polymer.

3.4. Step 4: Production chain design

Thanks to the previous step, the products that the urban industry needs to import in Grenoble have been highlighted: wood, textile fibers, metal bobbin, and polymer pellets. Here, the goal is to model the factory.

Fig. 3 illustrates the flows and a draft functioning of the urban factory. First, raw materials are imported. Then, materials are transformed by saw, sandpaper, 3D printer, weaving loom, sewing machine and shaper to become final products.

The number of each required machine has been calculated based on the following assumptions: (1) the urban industry must manufacture basic hygiene and life products for x persons, (2) the industry is running 24 hours a day, 365 days a year, (3) n is the number of products needed by one person for a year (functional unit), (4) t is the time to produce one unit of the product with one machine (hours). Consequently, the quantity to produce per hour (N) can be deduced thanks to equation (1):

$$N = \frac{n \cdot t}{261 \cdot 24} \cdot x \qquad (1)$$

A 3D printer with a speed of 165mm/s was considered. The diameter of the filament is 1.75mm and the density 1.24g/cm3; the mass flow rate is about 1.77kg/h for the 3D printers. A weaving loom is assumed to weave 7kg/h of yarn, and sewing machine is assumed to sew 7kg/hour. For saws, the time needed for sawing each piece is estimated separately, same for the metal shaper. Finally, by calculating the totals, the number of machines needed in two cases is obtained in Table 1. Two cases were considered: case A considers 100,000 inhabitants, this is the equivalent of Grenoble inhabitants; case B considers 600,000 inhabitants, this case is simulating Grenoble and its agglomeration inhabitants.

Table 1. Number of machines needed.

Machine	Case A	Case B
Saw	12,5	75
Metal shaper	0,1	0,3
3D metal printer	0,03	0,2
3D polymer printer	0,1	0,4
Weaving loom	12,1	73
Sewing machine	12,1	73

Case A seems feasible in an urban zone regarding the low number of machines needed. This would not take up so much place. To optimize the 3D printers and the metal shaper, it might be possible to add more printable products. Case (b) seems feasible at a higher scale but, it would be preferable to implement several urban industries in the whole agglomeration to remain in the goal of preventing commuting. An additional space could be added in order to sell the products directly from the urban factory.

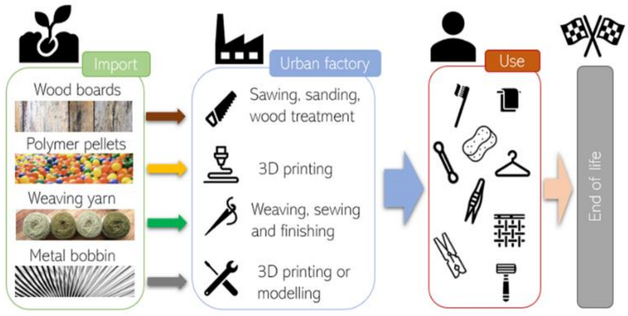

Fig. 3. Urban factory working concept.

Step 5: Environmental screening with LCA

This analysis aimed to assess how the implementation of an urban factory in Grenoble could impact the environment. The reasons for this analysis were the following: (1) to study the environmental impact of the urban industry, (2) to compare the impact of an urban industry with those of a classical industry, (3) to verify that an urban plant implemented in the Grenoble ecosystem could have less negative impacts on the environment than the current industry, (4) to become aware of the most impacting processes and products in the hygiene industry and (5) to design the production chain and products to be more sustainable.

The studied system was composed of two scenarios. The first one was the designed industry detailed in previous paragraphs. The second scenario was the scenario of the classic factory as it currently exists. In this simplified Life Cycle Analysis (LCA), only the life cycle of the manufactured products was considered. The construction of the industrial infrastructure was not taken into account.

The chosen functional unit was "to meet one person's needs for hygiene for 1 year". In this study, when products in different scenarios are used in the same way, the utilization time or consumables were not considered in the LCA calculation. For example, a toothbrush, reusable or not, needs the same amount of water and toothpaste during its use. As the goal was to compare the different scenarios, this energy utilization would be compensated in each part. In contrast, a disposable tissue does not need to be washed whereas a reusable one needs it. In this case, the washing impact of the reusable product was considered. The energy used in Grenoble is assumed to be high intensity hydraulic electricity.

In the urban factory scenario, the limited data of EcoInvent database have sometimes prevented us to design the product exactly as wanted in the material choice scenario. For instance, textiles are limited to cotton, kenaf and, jute. There were no organic fibres. Besides, the wood is not specified, and it is named "cleft timber". However, there is clef timber in Switzerland and in the rest of the world, so a little difference between the two scenarios has been made.

To obtain a quick comparison between both scenarios, single score was used. The result obtained for the classic industry is 25mpt with all the midpoints contribution addition against a score about 2mpt for the urban factory.

Consequently, it seems that an urban factory could have impacts 12.5 times lower than a conventional factory.

More specifically, same impacts are predominant in classic industry than in urban one, as shown in Fig. 4. Indeed, the two main impacts categories are freshwater ecotoxicity and human toxicity (cancer effect).

In addition, when comparing only the single score for a quick overview with the ILCD method, the urban factory is better on the three endpoints with a ratio of 9 times better for human health, 11 times for ecosystem and 55 times for resources. In the classic factory, the main contributors are bath towel, paper towel, sponge, make-up remover, cotton bud, sanitary towel, and tissue. All the products made by cotton, paper and viscose seems to be very detrimental to human health and to ecosystem. Regarding the urban factory, products with the major contributors are the bath towel, the sanitary towel, the tawashi sponge, the bathmat, and the beech razor. Here again, cotton crop is the main contributor.

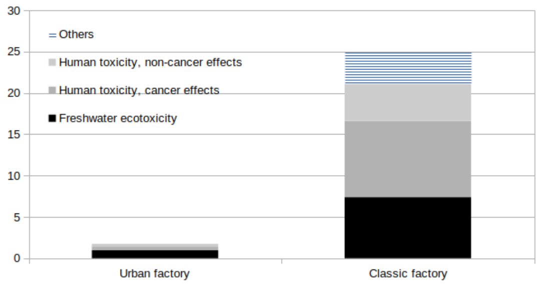

Fig. 4. Results of the environmental screening for urban and classical factories.

Waste reduction is the main difference between the urban factory and the classic industry. Wherever possible, the usual disposable version has been replaced with reusable versions. In this way, a large amount of waste is avoided. The washing process that will be used for reusable products during the use phase is not contributing a lot for bad impacts. Fig. 5 shows that the classic factory emitted 5.4 times more waste per year. We can also assess that there is almost no use of polymer in the urban factory because we avoid it and when polymers are used, it is with additive manufacture. Additive manufacture is also a way to spare material and reduce waste.

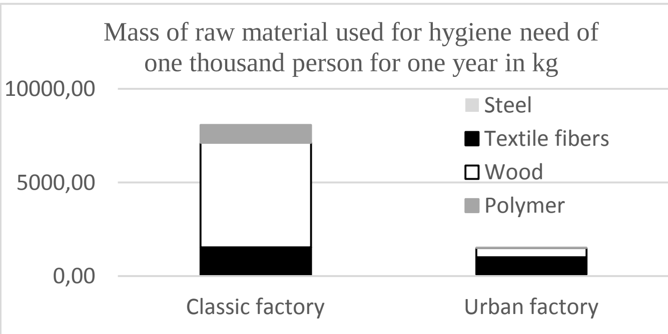

Fig. 5. Hygiene waste of 1000 persons for one year.

Polymers and paper seem to have high impacts and might be improper to be used in an urban factory, in this example. This is the reason why we have focused to avoid them in the urban factory scenario. Steel is to avoid as far as possible because it has a strong bad impact on human health. Viscose, from the sponge, reduces the mineral resource availability. All these materials are avoided as much as possible in the urban industry.

As the first big change in urban factories is to produce locally, the main journey of products or importations from across the world are avoided. This is important because it can be a gain in time and in quality. Some materials are brittle and the journey may affect their quality. In addition, by producing inside the country that will consume, the working conditions would be same that those of consumers, it could avoid labour exploitation. Finally, when going through a crisis such as the one we just went through (COVID-19), the fact that each country can live in self-sufficiency seems important. However, in the same way that relocation of factories from developed to developing countries had had important social consequences, the opposite move may also impact developing economies. This aspect should therefore be closely studied to anticipate these consequences. Moreover, the acceptability for consumers to change some habits would also need further attention.

The use of cotton turns out to be very detrimental for the environment and health, even with recycled cloth in the urban factory scenario. Probably, the alternative textile fibres studied in the textile part could be a great alternative and breakthrough in this industry (e.g. nettles). This is the reason why the most impacting product in the urban industry is the tawashi sponge. The assumption made is that this sponge is made with recycled cloth, 55% is already used cloth and 45% new fibres. However, tawashi sponge is, normally, made only with old clothes that are no longer in use. If this assumption were made, the impact of tawashi sponge could be even lower.

The toothbrush bristles are in PA6 in the two-scenario studied, however, PA4 could be great alternative because it has the same properties as PA6 but is compostable. [12]

Urban mining was quoted in the literature review but not applied in this study. However, the consideration of urban mining is promising and will avoid even more waste and raw material extraction. In addition, implemented urban factory that manage the end of life product will ensure a good valorisation of products. Probably that such scenario will bring closer the idea of closed cycle from circular economy.

3.5. Step 6: Technical and economic assessment

The urban factory seems to stand out positively in all the aspects studied. It would then be legitimate to ask: “Why does it not exist yet?”. To try to answer this question, technical and economic aspects of such a structure need to be studied. This would be the topic for future projects, but a few elements of answer arise. As labour in France is more expensive than in other countries, one can easily assume that all prices will rise. For example, if one buys boards from a sawmill near Grenoble, they will undoubtedly be more expensive than when bamboo is brought in from China. Just as textile weavers and seamstresses operate in Bangladesh, a seamstress paid in France will cost much more. So, the inhabitants would have to agree to pay slightly more for the assurance that they have not exploited anyone and that they have contributed to reducing human impact on the planet.

The 3D printer is still slow for mass production. In this scenario, this is not a problem since we have managed to replace every polymer or metal part that would be big with other materials. However, if we imagine that more products in polymers are produced, the delay could be a bit longer. As it is said in the above paragraph, manufacture time would probably be longer. To deal with this delay, a reorganization of the business model should be undertaken. For example, one could imagine that some printed products could be customised but then a delay would be necessary before purchase. One could also imagine making large series of each product at different times. This would require a concrete operating plan and the approval of the inhabitants.

Locally, economic impacts could be expected. For example, small businesses might be at risk of closing because of the competition of the urban factory. Seen from a certain angle, the urban factory could be detrimental to existing trades, and a study should be done to see if these people working in small businesses would be willing to change trades to work in the urban factory, for example.

Moreover, if we think about self-sufficiency, we will have to see whether all countries would be able to put such programs in place. Indeed, the transfer of work could cause developing countries to lose their sources of money. Thus, ethical questions must legitimately be studied. Besides, customer acceptance is a key argument to know if this urban industry would be viable economically. The customer acceptance concerns different aspects: the fact to have an industry in the urban city (noise, pollution, place…), the fact to have new functioning products should certainly be ordered in advance, it would not be a snapshot as when you go to the supermarket and finally the fact to give back the products in end-of-life to be sure that they will be recovered at the best.

4. Conclusion

This article presents a method to help design about factories, based on the identification of a need, and basic products to fulfil it. Another aspect is to identify the most suitable materials according to their physical properties and environmental impacts. Once the product components are defined, means to manufacture them can be designed. At this stage, the scenario is totally detailed, and the Life Cycle Assessment tends to prove the positive impact of the urban factory. In particular, urban factory could reduce waste and transportation. This is also due to the product lifespan that have been extended. The limitations of the urban factory are economic because the work labour is probably more expensive and the acceptability to change consuming habits, but this would require additional investigation. The manufacture time is also a limiting factor, and the assessment of the number of machines to satisfy the needs of a populated area is essential to ensure the relevance of urban factories.

Further research will be necessary to assess the industry organization and the acceptance of the local inhabitants. Finally, the ethical dilemma is to assess the impact of urban factories for both developed and developing countries, and for the rural areas.

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