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2.5 TUT-microfactory – a small-size, modular and sustainable production system

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Abstract
Micro and desktop factories are small size production systems suitable for fabricating and assembling small parts and products. The development originates in the early 1990's Japan, where small machines were designed in order to save resources when producing small products. This paper introduces the modular TUT-Microfactory concept, developed at Tampere University of Technology during the past 15 years, and its applications. The sustainability of miniaturized production systems is discussed from three perspectives – environmental, economic and social. The main conclusion is that micro and desktop factories can remarkably enhance the sustainability of manufacturing from all these three perspectives.
Keywords:
Desktop factory, Microfactory, Modular production system, Sustainable manufacturing, TUT-Microfactory concept

1 INTRODUCTION

Manufacturing industry is heading towards two paradigms: *Sustainable production* and *Adaptive production*. On one hand the manufacturers need to be able to produce clean, green products and consider the ecological footprint of their production. On the other hand they need to be able to produce customized products at low cost on demand and survive with the issues of demand fluctuation, small batch sizes, short product lifecycles, global manufacturing, rapid emergence of new technical solutions and ageing workforce, while simultaneously maintaining productivity and good quality. These constantly changing requirements call for adaptive and rapidly responding production systems that can quickly adjust to the required changes in processing functions, production capacity and distribution of the orders. Dynamic response to emergence is becoming a key issue in manufacturing field, because traditional manufacturing systems are built upon rigid architectures, which cannot respond efficiently and effectively to this dynamic change. The Factories of the Future (FoF) initiative [1] aims to support European industry in meeting an increasing global consumer demand for greener, more customised and higher-quality products by helping it convert to a demand-driven industry with better adaptivity, lower waste generation and smaller energy consumption.

Miniaturization of products has been a strong trend already for several years. As the parts are getting smaller and smaller, at least partial automation of the processes will become compulsory. Although the need for such production of small-sized products has been rapidly increasing, the size scale of the manufacturing systems has not changed much. Small products are still being produced with relatively large machines, which leads to inefficient space utilization and unnecessarily high operating costs. Furthermore, these large-size production systems and machines do not provide flexibility in their location, but need to be placed in traditional large factories even though, in many cases, it would be desirable to produce the products closer to the customer.

The authors believe that small-size production systems, micro- and desktop factories, can answer to the industrial demand and challenges discussed above. Micro and desktop factories are small-size production systems suitable for the manufacture of small products with micro and/or macro size features. The development originates from the early 1990's Japan, where small machines were developed in order to save resources when producing small products, and to reduce the size of the machinery and systems to match the product dimensions. In this context, "micro" does not necessarily refer to the size of parts or their features, or the actual size or resolution of the equipment. Instead, "micro" refers to a general objective of downscaling production equipment to the same scale with the products they are manufacturing. [2]

In the late 1990's, the research spread around the world, and since then multiple miniaturized production systems, i.e. micro and desktop factories (e.g. [3][4][5][6]), modular microfactory platforms (e.g. [7][8][9]) as well as miniaturized production equipment in general, including e.g. desktop-size machining units (e.g. [10][11]), robotic cells (e.g. [12][13][14]) and rapid prototyping units, have been developed. Despite of large amount of research cited above, the level of commercialization and adoption of microfactory solutions remains still relative low. The discipline lacks of empirical cases and industrial practice on microfactory-related business. However, few commercial desktop factories have been developed (e.g. [15][16][17]). Small-size machining units exist (e.g. [19][20]) and desktop-size stand-alone automation units have been developed for different purposes (e.g. [21][22][23]).

The micro and desktop factories can bring multiple benefits against the conventional factories in terms of their sustainability. This paper will first introduce the TUT-Microfactory concept and show examples of its applications. The main emphasis on this paper is put into describing how microfactories can contribute to the sustainable manufacturing. Three most common sustainability

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perspectives are viewed, namely ecological, economic and social.

2 INTRODUCTION TO TUT-MICROFACTORY CONCEPT

Tampere University of Technology (TUT) has a strong background on microfactory research since 1999. In this section the TUT-microfactory concept and some of its applications are introduced.

2.1 TUT-Microfactory concept

The TUT-Microfactory is a modular construction kit type concept with easy and rapid reconfigurability for different manufacturing processes of hand held size, or smaller, products. The system structure is designed with an idea that a base module (Figure 1) can work as an independent unit including all the needed auxiliary systems. The base module includes a clean room class work space, a control cabinet and the equipment needed by the clean room. Since the production module does not need a separate control cabinet, the factory can be aggregated fast and easily on a desktop table or other flat surface. This and small size of the modules enable extreme mobility of the production capacity. The outer dimensions of one base module are 300 x 200 x 220 mm and the inside workspace is 180 x 180 x 180 mm. [9][4]

The production module can be tailored to certain processes by placing process modules on top of the base module. Process module can be e.g. a robot, laser or machining unit. In addition to the top side of the base module, both sides and the front side can be left open when adjacent cells compose one integrated work space. Feeders and other devices can be placed in the opening on the sides. Examples of different configurations of TUT-microfactory modules can be seen in Figure 2. [9][4]

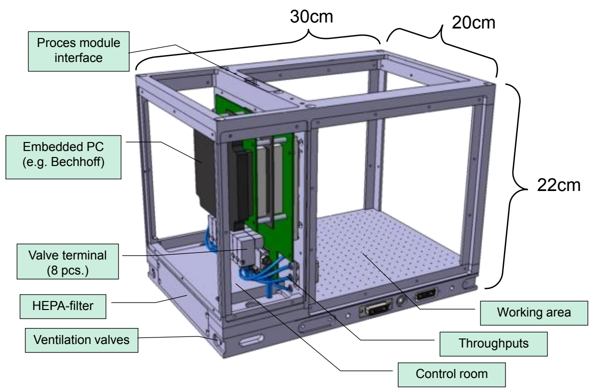

Figure 1: TUT-Microfactory base module.

All interfaces in the TUT-Microfactory concept have been designed to be as simple as possible. The base modules can be locked next to each other side by side, front by side, or front by front allowing nearly unlimited number of factory layouts, ranging from a simple line type to a freely branching one. The physical interface between two base modules includes two hybrid connectors for electrics/electronics, an interlocking system and connectors for pressurized air and vacuum. [9][4]

Due to the modular structure of the TUT-Microfactory concept and plug-and-play interfaces of the modules, it is easy to reconfigure the system to different product requirements. This reconfigurability is also supported by the fact that the small size and light weight equipment can be lifted manually without any lifting aids.

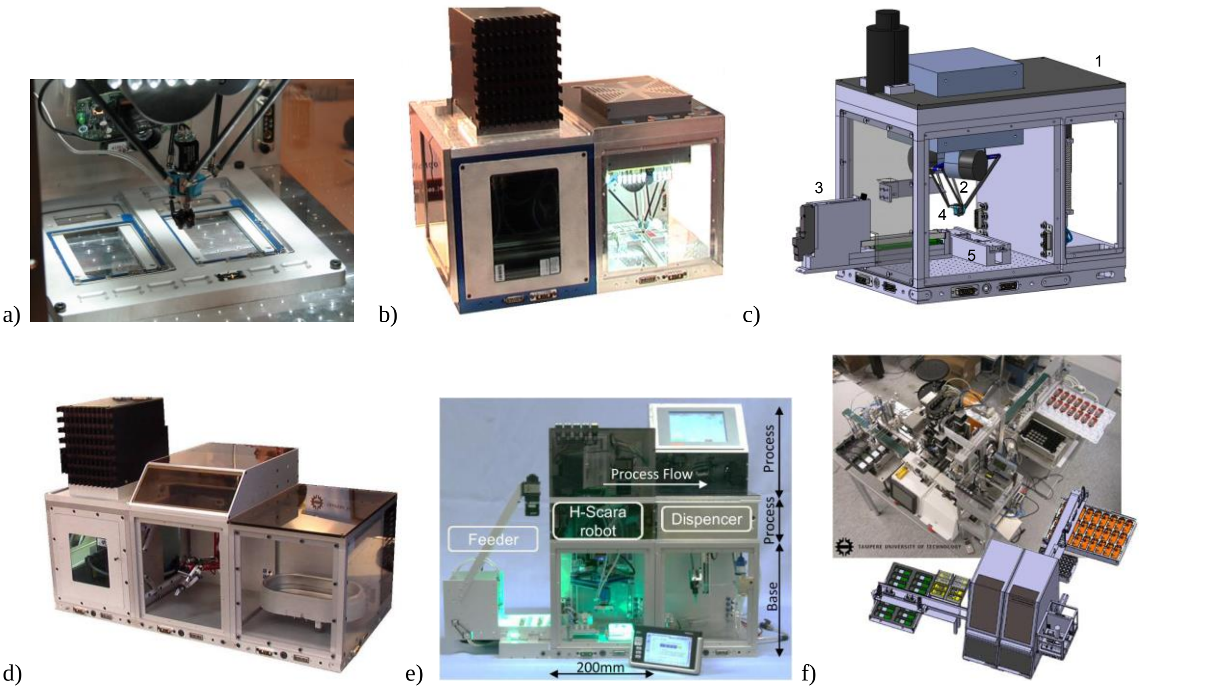

Figure 2: TUT-Microfactory applications: a) a loudspeaker assembly, b) laser marking, c) spring assembly, d) manufacturing of medical implant, e) gas sensor assembly, f) cell phone assembly. [26]

2.2 Applications of TUT-Microfactory concept

Several demonstrations, some of those shown in Figure 2, have been realized with the TUT-Microfactory concept during the past and ongoing research projects. One of the first case processes was assembly of a cell phone loudspeaker in 2005 (Fig. 2a). The assembly operation was a pick and place operation of the loudspeaker from a jig to the cell phone cover. The component size was 10.9 x 7.4 x 2 mm and weight less than 1 gram. As a manipulator a PocketDelta robot from Asyril [22] was used. [24]

The laser marking microfactory (Fig. 2b) was built as a demo for the Laser 2007 fair in Germany. The case products were personalized aluminium business cards with sizes of 4x9mm and 9x20mm. The case was a good introduction to the point-of-need manufacturing. The visitors could personalize their own business cards and get them manufactured right away. [4]

As a part of the Desk project, in 2008, the first industrial demonstration was conducted. The case process was a small spring placement in a MEMS sensor component (Fig. 2c). The small size (D 0.7 mm, L 2.54 mm) and complex shape made the spring extremely difficult to handle. The factory was built using only one TUT-Microfactory module. Besides the base module (1), a PocketDelta robot (2) was used as a manipulator, and the springs were fed by a machine vision based flexible feeding system, the Wisematic Minifeeder™ (3). The vacuum gripper (4) had a fiber optic sensor to detect the spring in the gripper. In addition, a small lead frame stepper (5) was designed to move the base components. The stepper used pneumatic actuators and an optical sensor to detect the position of the lead frame. [4]

The first process chain level three-cell demonstration was a manufacturing process of a medical implant, a laser-machined silicon rubber ear tube (D 3mm, L 5mm) (Fig. 2d). The manufacturing process consisted of machining and cleaning. Three base modules and two process modules were used in the demonstration. The first module included a 20W laser lathe with a scanner and an on-line inspection system. The on-line inspection system was used for measuring the dimensions of the tube. The second module included a 5 DOF articulated joint robot, which reached the adjacent cells as well. It was used to load the lathe and move the implants to washing. The final module included an ultrasonic washing system. [9]

The gas sensor assembly was a good introduction to different joining processes (Fig. 2e). The case product was a gas sensor (L 78mm, D 12mm), including two identical plastic frame parts, a detector in a metal package and an exciter. There were three phases in the assembly process. First, the detector was placed in the plastic frame in right orientation. Second, the exciter was placed in a correct position and angle. Third, another plastic frame was glued on top of the other. The microfactory assembly system consisted of two TUT-microfactory modules and a machine vision based flexible feeder for the frame parts. The first microfactory module was responsible for the part handling and assembly operations. A new TUT H-Scara robot was used for the manipulation. Besides the robot, the cell included a vacuum gripper, two standard 2-inch trays for component feeding, a turning unit and cameras. The second microfactory module provided the gluing process. It consisted of a low cost Cartesian TUT Linear Motor robot, a dispensing valve, an assembly jig for the base frame, a controller and an HMI unit. [25]

In the Mz-DTF project (2009-2010) the factory level integration of microfactory modules was considered and implemented. As a demonstration, a complete mobile phone assembly line was built out of commercial components and the TUT-Microfactory modules (Fig. 2f). The assembly process consisted of pick-and-place manipulation and screwing operations. The TUT-Microfactory module was used as a flexible screwing cell and larger desktop prototypes from industrial partners were used for the pick-and-place operations. The implementation was successful, but also some challenges came up. Even though handheld-size products fit perfectly into the TUT-Microfactory, the subcontractors in the electronic industry still tend to use rather large trays. Compact feeding systems, e.g. tape-and-reel, bowl and machine vision based flexible feeding, need to be further developed and accepted as an industry standard. [26]

3 SUSTAINABILITY OF MICROFACTORIES

Competitive Sustainable Manufacturing (CSM) calls for the sustainable development of manufacturing from different perspectives, most commonly mentioned being environmental, economic and social. According to [27], CSM must respond to:

- Environmental challenges, by promoting minimal use of natural resources and managing them at the best while reducing the environmental impact;
- Economic challenges by producing wealth and new services ensuring development and competitiveness through the time;
- Social challenges, by promoting social development and improved quality of life through renewed quality of wealth and jobs.

The following sections analyse how microfactories can enhance the sustainability of manufacturing from these three perspectives.

3.1 Environmental perspective

The modern production systems are expected to minimize the environmental loads the system causes during its lifetime. This sets requirements especially for the energy and resource consumption, emissions and waste generation, as well as reusability and disposal of the production system and its components.

The microfactory platforms comprise of small sized production devices. According to [2] and [31] compared to traditional larger factories, they require less factory floor space, consume less energy and raw material, and create less waste and emissions. Due to the smaller size of the overall factory, also less energy is needed for lighting, air-conditioning and heating. Also less waste heat, which needs to be cooled down, is generated.

Energy saving is one of the most often cited advantage of micro and desktop factories. For example, Kawahara et. al. [28] estimated that downscaling equipment to size 1/X reduces the consumed energy by factors presented in Table 1. They separated the energy consumption to three categories: 1) Operating energy, which is proportional to moving the parts of the equipment; 2) environmental energy, which is affected by the space needed for the equipment and the number of operators; and 3) process energy which is needed to remove material from the work piece (e.g. cutting, grinding). As can be seen from Table 1, majority of the energy is used for illumination and air conditioning and these also have the largest potential for energy savings. On the other hand, according to [28], the needed processing energy does not decrease at all when miniaturizing the equipment.

Table 1: Average energy consumption in actual factories and energy saving effect when the factories are miniaturized to 1/X [28].

	Average consumption in actual factories [%]	Energy-saving effect (1/X miniaturization)
Operating energy	13	$1 / X^3$
Environmental energy		
Illuminating	23	$1 / (1.5 * X^3)$
Air-conditioning	56	$1 / (3 * X^3)$
Processing energy and others	8	1

The case studies conducted in 2003 in Japan proved high potentials in energy and space savings by microfactories. A Desktop Factory by Sankyo for assembling motor bearings was reported to reach 98% savings in energy consumption and 95% reduction in space consumption compared to their traditional production systems [11].

Further empirical evidence of the reduced power consumption of miniaturized resources was obtained in a study conducted at TUT in 2010 by [29]. During the study average electrical power consumption of five different machines was measured in different states. The machines were: Hisac 500 OF assembly cell, Stäubli RX60 robot (with Adept controller), Mitsubishi RP-1AH, Schunk desktop scara prototype robot, and prototype of current Asyril Pocket Delta robot. The first two machines (Hisac and Stäubli) are "conventional size" machines, Mitsubishi and Schunk are small enough to be placed on a desktop, and Pocket Delta is a truly miniaturized parallel kinematic robot which can be integrated into TUT Microfactory module. Hisac, Stäubli, and Mitsubishi are commercial machines, while Schunk and Pocket Delta are prototype versions (Pocket Delta has since been commercialized by Asyril [22]).

The measured states were: 1) machine on, but motors disabled; 2) motors enabled; 3) machine running 5 x 25 x 5 mm and; 4) machine running 25 x 250 x 25 mm pick-and-place work cycle at machine's maximum speed with zero payload. Figure 3 shows that the most energy consuming machine was Hisac cell while it was running the long pick-and-place work cycle. What is worth noting is that Mitsubishi only used about 1/6th of Hisac power consumption while it was actually faster than Hisac as shown by Figure 4. This means that with the same amount of energy, Mitsubishi can perform over six times more movements than Hisac. Power consumptions for Schunk and Pocket Delta are not directly comparable since Schunk was considerably slower than the rest of machines and Pocket Delta's payload is only a fraction of others (around 8 g versus at least 1 kg for Hisac, Stäubli and Mitsubishi).

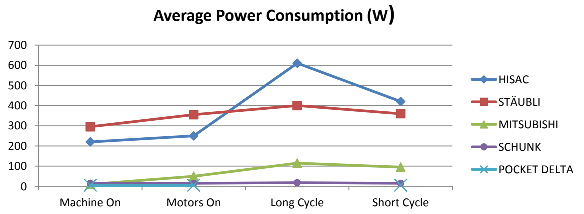

Figure 3: Average power consumption of the tested machines in different states [28].

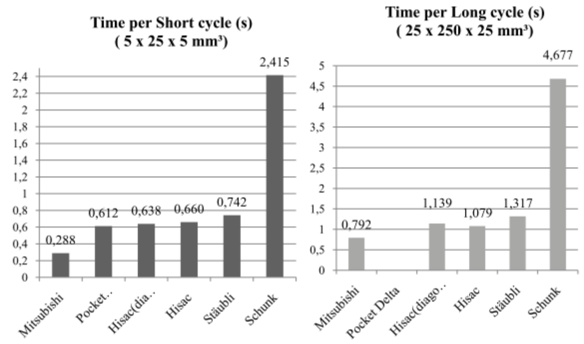

Figure 4: Cycle times of the tested machines with short and long cycles [28].

The measurements taken in TUT [29] do not directly support the estimations of Kawahara et al. [28] about the amount of energy saved. However, they do indicate that there is a great potential for operating energy savings and possibly even greater savings in, for example, air conditioning. Therefore, it can be assumed that the environmental impact is smaller for products manufactured in small size microfactories, compared to those manufactured in traditional factories.

3.2 Economical perspective

The economy pillar of the CSM calls for economic growth, global competitiveness and capital efficiency of manufacturing. From the European manufacturers' perspective the production with the future production systems need to be cost efficient in order to be able to compete against manual work performed in the low labour cost countries.

The micro- and desktop factories offer an affordable solution to manufacturers, because of lower investment and operating costs compared to traditional larger factories. Same manufacturing capacity can be fitted into smaller space and there is a possibility to use microfactory automation to aid human worker without the need to reserve huge, expensive factory spaces. Due to their small size, microfactories don't need big factory halls requiring heating, lighting, air-conditioning and so on. Also, as discussed in the previous section, the energy consumption and waste generation of the system itself is much lower compared to traditional larger-scale systems, leading to substantial savings in the operating costs. Microfactories allow also special controlled environment, such as a cleanroom, to be built into a small module space, eliminating the need for big expensive cleanrooms. Experiences from one full-scale desktop factory, realised in Takashima Sangyo in Japan, have shown remarkable competitiveness improvements compared to the company's earlier traditional factory: investment 1/5 and running costs 1/5 with the same production capacity [30].

In the era of customization, the desire of the manufacturers is to be able to cost-efficiently serve the customers in their individual demands and to bring the manufacturing closer to the customer. Due to the plug-and-play interfaces of the modular microfactory system components, the full scale system can be rapidly build and reconfigured to different functional and volume demands. The system set-up and ramp-up time and engineering effort for new process requirements can be radically reduced.

Especially for SMEs and start-ups circumstances like cleanroom, quality, skilled workers and investments in high-level equipment are predominant strategic and economic factors that hinder them to upscale from the lab to the full production. In addition, the unknown response from the market after launching the product, the lifecycle of the product and the evolution of the product are other issues that are taken in account when setting up the commercial production. Thus, such a modular and mobile microfactory increases the ability to rapidly follow the market dynamics by means of fast production and delivery of customised final products. Such a mobile mini-factory could also be leased (hired) for a time by a company preparing the launch of a new product, a start-up, a research institute, etc. Microfactories offer flexibility to try out new ideas without huge investments.

Small-size equipment provides improved portability of the production capacity to the place where it is needed, thus enabling new business models as well as production and logistic strategies. With the novel microfactory solutions the production doesn't need to be located anymore to traditional factories, but can be brought to the most convenient location. Few examples could be: fabricating customized shoe soles or assembling customized watches in a retail shop, fabricating spare parts in a battlefield, manufacturing products in a ship while being transported, building prototypes in an office room, teaching students about production systems in a classroom, or fabricating customized medical implants in doctor's operating room in hospital. This allows faster response to the customer requirements and more personalized service. In case of consumer products, the fact that customer can see his/her product to be manufactured or assembled, can bring competitive advantage against competitors and especially manufacturers abroad.

As discussed in the previous section microfactory can be considered as more environmental friendly way of production compared with the traditional production systems. The environmental awareness of the consumers is constantly increasing and the ecological footprint of the products starts to be more and more significant factor guiding the purchase decisions. Therefore products produced with "green" microfactories can win the game against similar products produced with traditional production systems. Implementing microfactory solutions is expected to offer potential for competitive advantage and attracting new environmentally aware customers.

3.3 Social perspective

The microfactory solutions could also have a wider societal impact for Europe and European manufacturing. First of all, they can create more attractive and safe workplaces. Secondly, they offer possibility to maintain the manufacturing jobs or even bring them back from low labour cost countries by enabling cost-efficient production of customized, green products on the spot.

From the social point of view it is important to minimize hazardous work environments, improve the ergonomics of the work environments and to pursue the efficiency, creativity and health of the workers. The risks of the manufacturing environment to the human worker are not only physical, but also psychological. For example, extremely simple, monotonous work can cause psychological issues and lack of motivation. Due to their small size, microfactories can be placed e.g. on the table of human worker to help him/her with boring repetitive tasks, tasks which require special accuracy, or tasks that are ergonomically difficult. The human can then concentrate on more interesting activities which require special skills. Compared with large production equipment, e.g. industrial robots, micro and microfactory solutions do not expose the human workers to danger. Due to small forces, for example the collisions are not fatal. Therefore, they enable safer human-machine co-operation compared to traditional large size equipment.

The microfactories can not only improve the manufacturing work environments, but also provide better service for the end customers. As the small size of the microfactory solutions allows them to be brought closer to the end customer, even to the point-of-sales or point-of-use, it ensures faster and more customized service and satisfied customers. The offered products can fit better to the individual customer's needs. For example, in the field of medical devices the customization is extremely important. Today, the customization of medical devices, such as medical implants, is still rare causing imperfect fit and possible complications. Therefore, the manufacturing of customized medical implants on the spot (in the surgeon's room or dentist's office) is expected to have a drastic impact on the quality of the implant customization and thus lead to a better fit of the implant in each patient's body. Therefore fewer complications are expected and consequently less expensive and possibly painful re-operations will be needed. This will lead to notable savings in healthcare costs and also in the time that is needed to treat individual patient. Also the quality of the treatment will be better resulting in increased well-being of the patients. Therefore, the societal impacts can be wide.

4 CONCLUSIONS

This paper discussed the sustainability of miniaturized production systems from environmental, economic and social perspectives. One microfactory concept, TUT-microfactory, was introduced in detail. As a conclusion, it can be said, that microfactory solutions can bring remarkable improvements to the manufacturing sustainability from all these three perspectives. The primary benefits are smaller investment and operating costs, as well as smaller energy and raw material consumption compared to conventional factories. The small size microfactories can be flexibly located to the most convenient locations, and modular concepts allow easy adaptivity to different demands. This adaptive "on the spot" manufacturing and the fact that microfactories are more environment friendly compared to larger factories, are expected to be the winning factors supporting the competitiveness of the European manufacturing against the low labour cost countries in the future.

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