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Micro and Desktop Factory Roadmap

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1 Preface

The target audience of this roadmap is firstly the Finnish manufacturing industry and machine suppliers and the national technology agency Finland - TEKES, which is also the financier of this study. The roadmap is also targeted to for companies and organizations working in the area of microfactories either as end users or component suppliers, both nationally and globally.

This work is conducted in TEKES project called “DeskConcept - Opportunities and Future of Desktop Production Concept”. The authors of this roadmap are researchers at the Tampere University of Technology at the Department of Production Engineering (http://www.tut.fi/tte/). The work is led by prof. Reijo Tuokko and TUT microfactory projects manager Riku Heikkilä (See http://www.tut.fi/microfactory/). Other contributors in alphabetical order are Eeva Järvenpää, Anssi Nurmi, Timo Prusi, Niko Siltala and Asser Vuola.

2 Summary

Terms desktop and microfactory both refer to production equipment that is miniaturized down to the level where it can placed on desktop and manually moved without any lifting aids. In this context, micro does not necessarily refer to the size of parts produced 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.

Academic research literature speculates with several advantages and benefits of using miniaturized production equipment. These range from reduced use of energy and other resources (such as raw material) to better operator ergonomics and from greater equipment flexibility and reconfigurability to ubiquitous manufacturing (manufacturing on-the-spot, i.e. manufacturing the end product where it is used). Academic research has also generated several pieces of equipment and application demonstrations, and many of those are described in this document.

Despite of nearly two decades of academic research, wider industrial breakthrough has not yet taken place and, in fact, many of the speculated advantages have not been proven or are not (yet) practical. However, there are successful industrial examples including miniaturized machining units; robotic, assembly and process cells; as well as other pieces of desktop scale equipment. These are also presented in this document.

Looking at and analysing the current state of micro and desktop production related academic and commercial research and development, there are notable gaps that should be addressed. Many of these are general to several fields, such as understanding the actual needs of industry, whereas some are specific to miniaturised production field. One such example is the size of the equipment: research equipment is often “too small” to be commercially viable alternative. However, it is important to seek the limits of miniaturisation and even though research results might not be directly adaptable to industrial use, companies get ideas and solution models from research.

The field of desktop production is new and the future development directions are not clear. In general, there seems to be two main development directions for micro and desktop factory equipment:

1) Small size equipment assisting human operators at the corner of desk

2) Small size equipment forming fully automatic production lines (including line components, modules, and cells)

These, and other aspects including visions of potential application areas and business models for system providers, are discussed in detail in this roadmap.

To meet the visions presented, some actions are needed. Therefore, this document gives guidelines for various industrial user groups (end users of miniaturized production equipment, system providers/integrators and component providers) as well as academia for forming their strategies in order to exploit the benefits of miniaturized production. To summarise, the basic guidelines for different actors are:

- Everyone: Push the desktop ideology and awareness of the technology and its possibilities. Market and be present at events where potential new fields get together. Tell what is available and what is needed.
- Equipment end users: Specify and determine what is needed. Be brave to try out new ways of doing things. Think what is really needed – do not over specify.
- System providers / integrators: Organize own operations and product portfolios so that supplying equipment fulfilling the end user specifications can be done profitably.
- Component providers: Design and supply components which are cost-efficient and easy to integrate to and to take into use in desktop scale equipment.
- Academia: Look further into future, support industrial sector in their shorter term development work and act as a facilitator for cooperation between different actors.

3 Introduction

The term microfactory originates from the research conducted in Japan in the 1990's. Research institutions, national universities and corporations developed smaller machines in order to produce micro parts and machines. Energy saving and economizing were some of the primary goals. (Okazaki et al, 2004). Very closely related term Desktop Factory® (or DTF®) is an officially registered trademark by NIDEK Sankyo Corporation. However, generally speaking and in this document both the desktop factory and microfactory refer to the same concept: Minimizing production equipment down to level where they can be placed on desktop and manually moved without any lifting aids.

It is worth noting that, in this context, micro does not necessarily refer to the size of parts or their features nor does it mean that even microfactories are actually measured in micrometres. Instead, microfactories can be seen as a general philosophy to minimize the production systems and processes to match the products in size (Okazaki et al, 2004). Therefore, in this document, micro and desktop production systems refer to micro and desktop factories as well as miniaturized production equipment in general, including e.g. desktop size machining units, robotic cells and rapid prototyping units.

In addition, according to our definition, micro and/or desktop factory is a production system that fits on a table, is mobile by human without lifting aids, is fully integrated (no external control cabinets), is preferably modular and can be utilized to manufacture small parts and devices (< 1000 cm^3). The lower boundary for part size is not fixed, but in practice it is in range of 1 mm^3. One of the main drivers for moving towards micro and desktop factories is bringing the size of production equipment closer to the size of the produced goods – and doing this in economically cost-effective way.

For several years the miniaturization of products has been a strong global trend. As technology continues to develop, products are getting smaller and more complex. Production processes have to be faster, more precise and more accurate. At the same time, the market calls for customer specific products leading to small batch sizes and short product lifecycles. Modularity, product customization and personalization increase amount of product variants and variation in production volumes. This turbulent production environment calls for adaptive and rapidly responding production systems that can adjust to required changes both in production capacity and processing functions. The production ramp-up has to be fast and the effort of changing the production system for the production of new products or different volumes is to be minimized. Customers are not anymore willing to pay more for the speed and flexibility. This means that the production systems need to be able to produce customized products with the price of mass products. Consequently, new production paradigms for more flexible production have been introduced, e.g. Lean, flexible, reconfigurable, agile and agent-based manufacturing.

In addition, following the new sustainable manufacturing paradigm, companies are moving towards more environmentally friendly production. Companies have started to think more about issues such as ecological footprint, energy consumption, use of resources and recycling. New production technologies have been developed to support the new production paradigms, and to meet the flexibility and ecological requirements of modern production.

For all these challenges, miniaturization of production equipment has been suggested as one solution. For example, construction kit type, modular micro production systems could provide tools for flexible and reconfigurable manufacturing as well as be used as a part of automation assisted manual work following Lean principles. In addition, the small size enables more production units to be fit into the same factory space compared with the traditional production systems.

However, even though production equipment miniaturization has been widely studied in academia, large scale industrial breakthrough has not yet been made. Many companies still stick to current ways of doing things by using conventional size machines and/or outsourcing basic manufacturing operations to low labour cost countries. Even though there are sporadic successful examples of utilizing miniaturized equipment, general awareness and acceptance of this new technology is still lacking.

In order to increase awareness of miniaturized production, this document presents the current state of micro and desktop size production research and commercialization giving examples of several commercially available pieces of equipment. Also authors' visions of the future development directions in the field will be discussed. Finally, authors give guidelines for both research and industrial user groups (end users of miniaturized production equipment, system providers and component providers) for forming their strategies for exploiting the benefits of miniaturized production.

4 Scope and Limitations

The context of this roadmap is micro and desktop factories - their present state and utilisation in future.

The objectives of this roadmap are:

- To identify actors and state-of-the-art in the field.
- To look for new ways of utilising microfactories.
- To identify new business areas.
- To draw a vision where the field is heading to.
- To state some of possible strategies for achieving the visions.

The roadmap is limited to micro and desktop factories. These are facilities and machinery fitting on table top.

5 Current State of Micro and Desktop Manufacturing

This chapter discusses the current state of micro and desktop manufacturing. It starts by listing the actors working with micro and desktop factory solutions. After that the development activities around the topic, both academic and commercial, will be reviewed. Finally the characteristics of different small-size components and supporting technologies will be discussed.

5.1 Actors Working with Desktop and Microfactories

Figure 1 presents the geographical distribution of different actors working in the area of micro and desktop manufacturing. The following chapters will list the actors in the research and academic world, as well as the three categories: System providers, equipment and component providers.

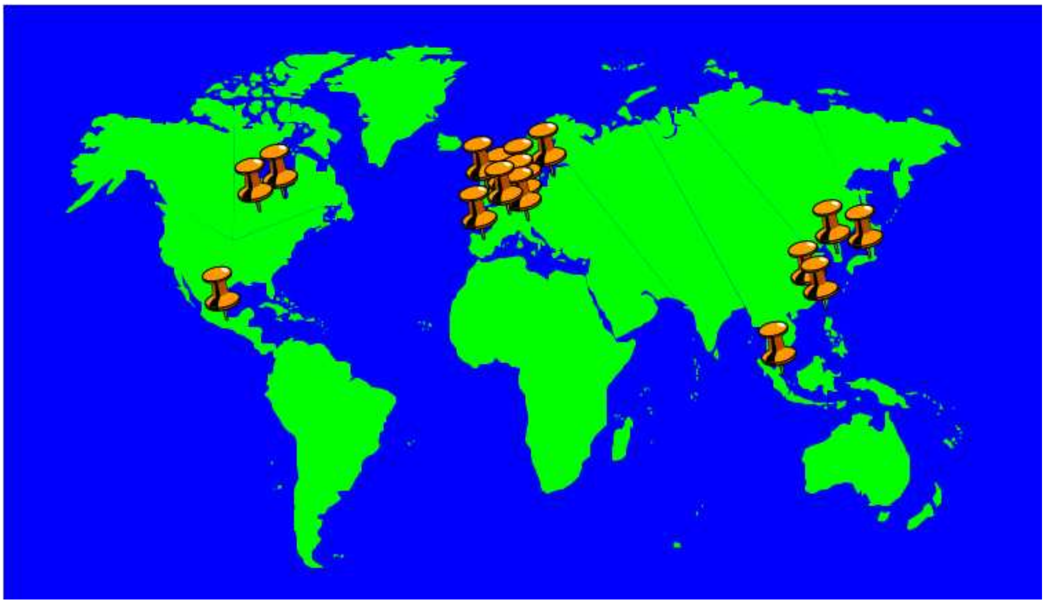

Figure 1. Worldwide desktop and microfactory related R&D activities (Okazaki, 2010b)

5.1.1 Research Centres and Universities

Table 1 lists research organisations that are active in micro and desktop factory related research.

Table 1. Research institutes and universities active in microfactory research

Country	Research centre/ university	City	Speciality/ papers/ concepts
Finland	TUT, Tampere University of Technology Department of Production Engineering	Tampere	Tuokko et al., 2000 (TOMI) Jokinen & Lastra, 2007 (ABAS) Heikkilä et al., 2010 (TUT Microfactory) http://www.tut.fi/microfactory/ Tuokko & Nurmi, 2011 (general information)
	VTT, Technical Research Centre of Finland		http://www.vtt.fi/proj/deskassy http://www.vtt.fi/proj/deskassy (DeskAssy project)
Germany	Frauenhofer IPA, Fraunhofer-Institut für Produktionstechnik und Automatisierung	Frauenhof	Gaugel et al., 2004 (AMMS)
	KIT, Karlsruhe Institute of Technology ● IAI, Institute for Applied Computer Science (i.e. AIA, Angewandte Informatic)	Karlsruhe	Bär, 2006 (µFemos) Hofmann et al., 2011(microFLEX) Pfriem et al., 2011 (fish sorting system)
Switzerland	MCCS, Micro Center Central Switzerland	Sarnen	Link between the industry and the politics (funding for ex. CSEM)
	EPFL, École Polytechnique Fédérale de Lausanne (Lausanne) ● LPM, Laboratoire de Production Microtechnique ● LSRO (former LSRO1 & LSRO2), Laboratoire de Systèmes Robotiques	Lausanne	Delta robotics Verettas et al., 2005 (microboxes) Kobel & Clavel, 2010 (rotary assembly line) Koelemeijer Chollet et al. 2002 (microassemlby cells), 1999, 2003a, 2003b (cost calculations)
	CSEM, Centre Suisse d'Electronique et de Microtechnique S.A.	Neuchatel	Micromechanics-related research (for watchmaking industry)
	HTI-Biel, Hochschule für Technik und Informatik (i.e. BFH, Berner Fachhochshule)	Biel	Before there was a common microfactory project between EPFL, CSEM and HTI-Biel (→Asyril)

France	FEMTO-ST, Franche-Comté Electronique, Mécanique, Thermique et Optique - Sciences et Technologies ● Multiple e.g. Department of Automatic Control and Mico-Mechatronic Systems	Besançon	Clévy et al., 2008 (micro assembly systems)
USA	CMU, Carnegie Mellon University ● The Robotics Institute	Pittsburgh	Rizzi et al., 2001 (Agile assembly architecture)
	UIUC, University of Illinois at Urbana–Champaign ● Department of Mechanical and Industrial Engineering	Illinois	Honegger et al. 2006a, 2006b (Illinois microfactory)
	NWU, Northwestern University ● Department of Mechanical Engineering	Illinois	Ehmann
Japan	MCC, Micromachine Center		Ataka, 1999; Ogawa, 2000 (first microfactory projects)
	AIST, National Institute of Advanced Industrial Science and Technology Formerly: AIST, Agency of Industrial Science and Technology ● MEL, Mechanical Engineering Laboratory		Kitahara et al., 1998 (portable microfactory) Kurita et al., 2001 (multifunction machines) Okazaki et al., 2001 (“El Chuchito” micro lathe) Okazaki, 2004 (micro lathe) Nakano et al., 2008; Ashida et al., 2010 (MEMS microfactory)
	DTF Research Consortium	Suwa	DTF Internal Forums on Desktop Factory in SUWA
	AMRI, Advanced Manufacturing Research Institute		Nakano et al., 2008; Ashida et al., 2010 (MEMS microfactory)
	TIRI, Tokyo Metropolitan Industrial Technology Research Institute	Tokyo	bilateral with AIST & new AIST
	Chiba University		bilateral with AIST & TIRI
Korea	KIMM, Korea Institute of Machinery & Materials ● Intelligent Machine Research Centre	Daejeon	Park et al., 2007 (Mosaic) + bilateral with e.g. TUT

Mexico	UNAM, Universidad Nacional Autónoma de México ● Laboratory of Micromechanics and Mechatronics		Ruiz-Huerta et al., 2004 (Mexican microfactory development)
Turkey	Mechatronics Engineering Sabanci University Istanbul ● Gebze Institute of Technology	Istanbul	Kunt et al., 2008 (micro assembly cells)

5.1.2 Component and Equipment Providers

Table 2 gives a short list of some component providers. The list is by no means comprehensive; instead, it shows the providers TUT research team has used during previous years.

Table 2. Component and Equipment providers TUT research team has used.

Technologies	Company	URL
pneumatic, electromechanical components (also smart cameras)	Festo AG/Oy	www.festo.com
motors	Elliptec AG	www.elliptec.com
motors	New Scale Technologies	www.newscaletech.com
motors, drives	Maxon Motors	www.maxonmotor.com
motors, drives	Faulhaber	www.faulhaber.com
drives	Elmo	www.elmomc.com
drives	Copley Controls	www.copleycontrols.com
motors, drives	Nanotec	en.nanotec.com
drives	Technosoft	www.technosoftmotion.com
grippers, interfaces, small robot	Schunk	www.schunk.com
sensors, ICs	Austria Micro Systems	www.austriamicrosystems.com
sensors	Heidenhain	www.heidenhain.com
sensors	Numerik Jena	www.numerikjena.de
stages/axis	PI - Piezo Nano Positioning	www.physikinstrumente.com
stages/axis	Piezosystem Jena	www.piezojena.com
stages/axis	DSM - Dynamic Structures and Materials	www.dynamic-structures.com
stages/axis	SmarAct	smaract.de
cameras	VRmagic	www.vrmagic.com/en
cameras	IDS Imaging Development Systems	www.ids-imaging.com
small robots	Mitsubishi	www.mitsubishi-automation.com/robots.html
small robots	IAI	www.intelligentactuator.com
precision manipulator systems	Piezojena	www.piezojena.com
precision manipulator systems	Kleindiek Nanotechnik	www.nanotechnik.com
precision manipulator systems	Klocke Nanotechnik	www.nanomotor.de
controllers and control HW	Beckhoff	www.beckhoff.com

5.2 Micro and Desktop Factory Development

According to Okazaki et al. (2004), the idea of a microfactory originates from the research conducted in Japan in the 1990's. The Micromachine Center (MMC) was established in 1988. Between 1991 and 2000, national universities, research centres and corporations worked on the project "Micromachines Technology". The research was based on an idea that smaller machines might be needed to produce micro parts and machines. Energy saving and economizing were the primary goals. Within the project, smaller machines and equipment were developed. Ideas of “desk-top”, “palm-top” and “mobile” factories were awoken. (Okazaki et al., 2004) Subsequently, different concepts of highly miniaturized production systems and machining units have been introduced. Afterwards, topics such as modularity (Gaugel et al., 2004), virtual models (Rizzi et al., 2001), cleanrooms (Verettas et al., 2005) and high-precision manufacturing (Clévy et al., 2008) have been included into microfactory research.

Micro and desktop factory are the terms normally used to describe highly miniaturized manufacturing systems and equipment. The terms “mini factory” and “factory-in-a-suitcase” are mostly historical. In other occasions, the same terms might refer to e.g. 3D-printing (DTF, 2011) and infrastructure software (Rosenthal & Schmitz-Homberg, 2008). Within the manufacturing research, the prefix micro might refer to micro-size manufacturing, small manufacturing equipment or both. Desktop Factory® (or DTF®) is an officially registered trademark by NIDEK Sankyo Corporation, which is a key member of the Japanese DTF Research Consortium.

The following chapters will first introduce the research conducted in the academic world followed then by the commercial solutions related to micro and desktop factories. In the following, we have grouped the different concepts in the desktop and microfactory field to four different categories: 1) miniaturized machining units, 2) miniaturized robotic and assembly cells, 3) sets of small-size production equipment and 4) modular microfactory platforms. In addition to the above mentioned categories, commercial 3D printers have been developed and they are also shortly introduced. Finally the gap between the research and commercial products will be shortly analysed.

5.2.1 Research Results and On-going Research

The following chapters introduce research results in the above mentioned four different categories of desktop factory equipment. These chapters are from the Master of Science thesis of Anssi Nurmi (2012). In addition to those, also some logistic concepts for microfactories will be discussed, followed by the research results evaluating the energy efficiency of micro and desktop factory solutions.

5.2.1.1 Miniaturized Machining Units

Parallel to other research efforts, multiple highly miniaturized machining units have been developed since the mid 1990’s. Some of them have been developed for the microfactory concepts described later in this chapter and some are developed for stand-alone use. They are usually high-speed and high-precision machines designed to produce metallic precision mechanics components. Terms such as “palm-top factory” and “mini factory” arose with the research. This section introduces six concepts seen in Table 3 and Figure 2.

Table 3. Academic miniaturized machining units

Year	CC	Concept	Institute	Source
1996	JP	Microlathe	MEL	Kitahara et al., 1998
1999	JP	Multifunction desktop machine	AIST	Kurita et al., 2001
2000	JP	NC Microlathe	AIST(MEL)	Okazaki & Kitahara, 2000
2001	JP	Desk-Top NC Milling Machine, 200krpm ("El Chuchito")	AIST	Okazaki et al., 2001
2004	JP	Desk-Top Milling Machine, 300krpm	AIST	Okazaki, 2004
2004	MX	Mexican First Generation MMT	UNAM	Ruiz-Huerta et al., 2004

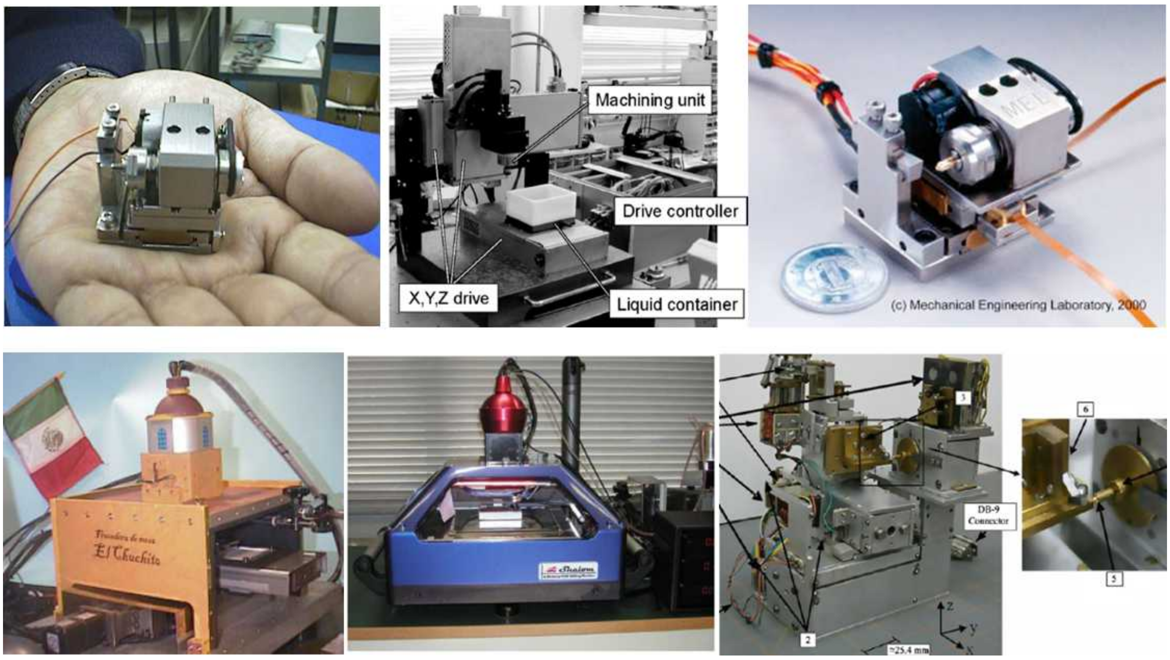

Figure 2. Micro lathe (Kitahara et al., 1998), Multifunction desktop machine (Kurita et al., 2001), Micro lathe with numerical control (Okazaki & Kitahara, 2000), "El Chuchito" (Okazaki et al., 2001), Desk-Top Milling Machine (Okazaki, 2004) and Mexican First Generation MMT (Ruiz-Huerta et al., 2004)

The first and one of the most commonly cited is the micro lathe developed in Japan in 1996. The lathe revealed the possibility to downsize machining units. The lathe has dimensions of 32x25x30 mm and it weighs 100 g. The main spindle motor uses only 1.5 W, and it can turn up to 10,000 rpm. It has an accuracy of 1.5 µm in the feed direction and a roundness of 2.5 µm. The minimum diameter of work piece is 60 µm. (Kitahara et al., 1998, according to Okazaki et al., 2004) Four years later, in 2000, the micro lathe was succeeded to equip with a precision digital control system. A desktop milling machining unit, with a footprint or 550x450 mm, was build based on the NC (numerical controlled) micro lathe. (Okazaki & Kitahara, 2000, according to Okazaki et al., 2004)

Downsizing also lead to development of high-speed spindles. "El Chuchito", developed by AIST, was one of the first miniaturized high-speed milling machines. It has dimensions of

450x300x380 mm and a maximum spindle speed of 200,000 rpm. It includes a numerical control system with 0.1 µm resolution. The total power consumption under high-speed machining is 120 W. (Okazaki et al., 2001) In 2004, the system was revised. The new machine includes a 300,000 rpm spindle. It is slightly bigger, having dimensions of 480x480x470 mm and a weight of 42 kg. The power consumption also rose up to 400 W. However, it is more accurate because of the linear XY stage. (Okazaki, 2004)

Downsizing machining tools also led to the development of multifunctional machining units. Just before millennium, a prototype of multifunctional machining unit was developed by AIST and new AIST. The machine has dimensions of 557x604x655 mm and a weight of 80 kg. There are five changeable machining units: high, middle and low speed spindles, laser irradiation unit and piezoelectric actuator unit. As a result, multiple machining methods are enabled: milling, drilling, cutting, grinding, polishing, EDM, ECM, laser machining and laser treatments. (Kurita et al., 2001)

Another example of micro machine development is the micro equipment developed in Mexico in the early 2010 decade. The first generation had dimensions of 130x160x85 mm and the second generation was slightly larger. They are based on small-size stepping motors. In order to decrease the price of the equipment, a lot of low-cost materials and only few commercial components were used. (Ruiz-Huerta et al., 2004)

5.2.1.2 Miniaturized Robotic and Assembly Cells

This sub-section describes the second category of academic microfactory concepts. Table 4 lists six and Figure 3 shows four robotic cells and assembly units. They are stand-alone and they usually have one or few manipulators and one or few cameras for tele-operation (they work in semi-automatic mode) or for process control.

Table 4. Academic miniaturized robotic cells and assembly units

Year	CC	Concept	Institute	Source
2002	CH	Flexible Microassembly Cell	EPFL (LPM)	Koelemeijer Chollet et al., 2002
2003	GER	µFemos	KIT (& IEF Werner GmbH)	Bär, 2006
2004	FIN	TOMI - Mini assembly cell	TUT	Uusitalo et al., 2004
2008	TR	Versatile and Reconfigurable Microassembly Workstation	Sabanchi University	Kunt et al., 2008
2008	FR	Flexible Micro-Assembly System with Automated Tool Changer	FEMTO-ST	Clévy et al., 2008
2011	GER	Robotic Systems for High Throughput Bio Analytics	KIT (AIA)	Pfriem et al., 2011

Figure 3. Flexible Micro assembly Cell (Koelemeijer Chollet et al., 2002), µFemos (Bär, 2006), Mini assembly cell (Uusitalo et al., 2004), Robotic Systems for High Throughput Bio Analytics (Pfriem et al., 2011)

One of the first micro assembly systems were the Flexible Microassembly Cells developed by EPFL in 2002. At the time, two cells were developed. Both of them have a working space of approximately 150x150x150 mm and one camera for vision system. They are designed for small and medium sized batches. The low-resolution cell has a 4 DOF robot with a resolution of 5 µm. The camera is integrated to the robot. The high-resolution cell includes a 6 DOF robot with a resolution of 0.5 µm and a 3 DOF robot for clue dispensing. The vision system is integrated into the Z-axis of the 6 DOF robot, keeping the gripper within the field of view all the time. The system was demonstrated by semi-automatic assembly of a watch plate. (Koelemeijer Chollet et al., 2002)

Some of the concepts include more automation and multiple processes in one cell. The µFemos was developed by KIT in Germany in 2003. The system includes a 4 DOF Cartesian axis system, i.e. XYZ and rotation. The dimensions are 600x600x500 mm. It was developed for assembly of an optical distance sensor with high precision. Multiple cells were sketched in line but it was not demonstrated. (Bär, 2006)

Mini assembly cell was designed for the assembly of mini-sized planetary gearheads in 2004. The system has a footprint of 500x500 mm. It was designed for the TOMI Microfactory. (Uusitalo et al., 2004) Another example is a Versatile and Reconfigurable Microassembly Workstation, developed by Sabanci University and Gebze Institute of Technology in Turkey in 2008. The desktop-size system includes two 3 DOF micromanipulator stages and a 3 DOF precision positioning system for the sample, as well as a vision systems with two CCD cameras with magnification of 4x-800x. (Kunt et al., 2008)

Two main concerns of micromanipulation are the fragile components and the sticky effect. As things get smaller, gravity becomes insignificant. Instead, adhesion and other surface forces become dominant. In addition, small parts tend to be fragile. As a result, vacuum grippers might destroy the small parts and releasing them becomes difficult. Therefore, more sophisticated grippers need to be developed. One example is the Flexible Micro-Assembly System developed by FEMTO-ST in France in the end of the 2010 decade. The desktop-size system includes a XYZ positioning table, a camera and specially designed piezoelectric gripper with an automated tool changer. The gripper includes two piezoelectric fingers. The positioning accuracy is about 3 µm. The system is tele-operated with a joystick and a screen. (Clévy et al., 2008)

At the moment, the Robotic Systems for High Throughput Bio Analytics is under development at KIT. According to Pfriem et al. (2011), the system is developed for recognition and sorting of zebrafishes. Currently the process of breeding, pipetting, microscoping and analysing is mainly manual. It takes approximately 45 minutes for a biologist to sort manually a fish per each of 384 chambers on a well plate. In addition to saving time, the system can maintain a constant temperature of 28°C. (Pfriem et al., 2011) The system reveals interesting potential in laboratory automation. Laboratory processes and bio analytics have a lot of repetitive tasks (e.g. pipetting), which are conducted fully manually.

5.2.1.3 Microfactory as a Set of Small Size Production Equipment

The original Japanese approach to microfactory is to develop a fixed set of integrated small-size production machines. The microfactory systems usually include miniaturized machining units and/or micro-press to produce the components, a small-size manipulator, transfer arm or conveyor system to transport the components and a small-size assembly unit or a micro-manipulator to assemble the components. The systems are usually tele-operated, i.e. the operator uses the machines via joystick, computer or other devices (see Table 5 and Figure 4).). In authors' point of view, the primary goal of the research has been miniaturization of the machines. As a result, versatile microfactory architectures and systems have been developed. Terms such as "factory-in-a-suitcase" and "portable microfactory" arose with the research.

Table 5. Academic microfactory concepts

Year	CC	Concept	Institute	Source
1994	JP	Microfactory by MMC or Experimental Microfactory System	MMC (& companies)	Ataka, 1999 Ogawa, 2000
1998	JP	Portable Microfactory or Desktop Machining Microfactory	AIST (MEL)	Kitahara et al., 1998 Tanaka, 2001
2000	FIN	TOMI Microfactory	TUT	Tuokko et al., 2000 Tuokko, 2002
2006	USA	Automated Illinois Microfactory	UIUC	Honegger et al., 2006a Honegger et al., 2006b
2006	KR	Mosaic	KIMM	Park et al., 2007

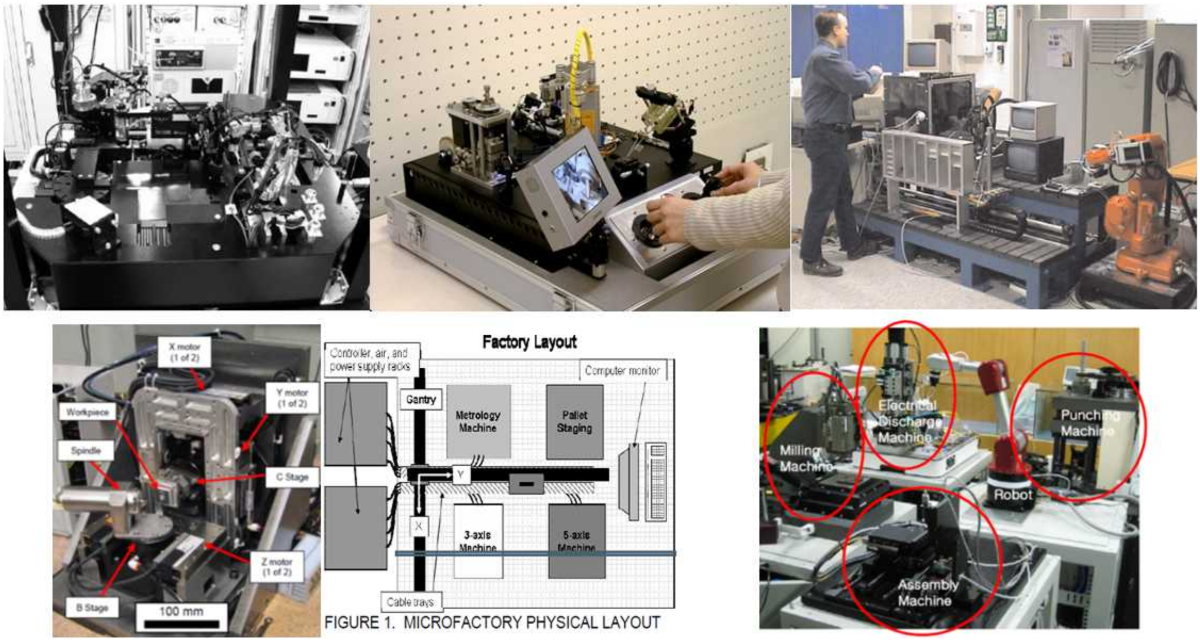

Figure 4. Microfactory by MMC (Ataka, 1999), Portable Microfactory (Tanaka, 2001), TOMI Microfactory (Tuokko, 2000), Automated Illinois Microfactory (Honegger et al., 2006a, 2006b) and Mosaic (Park et al., 2007)

The first microfactory concept “Experimental Microfactory System” was developed in Japan in the 1990’s. Dimensions of the system are 600x650x750 mm. It was developed e.g. for production of micro-mechanics. The system consists of a conveyance unit, a processing unit and an assembling unit. The assembling unit includes two micro-arms, a precise stage and several working tools. The processing unit includes an electrochemical machining device, micro-pumps and a recognition device. (Ataka, 1999) Another famous Japanese microfactory concept is the Portable Microfactory developed by MEL in 1998. Dimensions of the system are 625x490x380mm, and it is tele-operated. The user interface consists of two joysticks and a 5.8-inch LCD monitor, showing live video of three miniature CCD cameras. The system has a micro lathe, a micro-milling machine, a micro-press machine, a transfer arm and a two-fingered micro manipulator. Miniature ball bearing was used as the first case product. (Tanaka, 2001)

One of the first microfactory concepts outside Japan was the TOMI Microfactory developed by TUT in Finland in 2000. TOMI (Towards Mini and Micro Assembly Factories) was a pilot project for TUT microfactory research. The goal was to develop an integrated high performance assembly system of a miniature product. The case product was a planetary gearhead with a diameter of 8 mm and variable gear ratios. As a result, a small-size floor standing system was developed. Dimensions of the production system are 1800x500 mm and the system consists of modules of 500x500 mm. All the assembly phases were packed into one module. (Tuokko, 2002)

A concept of automated microfactory was developed at University of Illinois at Urbana-Champaign (UIUC) in USA in 2006. The system is based on a 900x900 mm pneumatic vibration isolated table. Individual machines locate horizontally on the table and they are operated by a computer. Machine development included a three-axis and a five-axis milling/drilling machines as well as a metrology station. Specific pallets were developed to transfer the parts. (Honegger et al., 2006a, 2006b) Korea Institute of Machinery & Materials (KIMM) developed their first microfactory in 2006. The system consists of a micro milling machine, an electrical discharge machine, a manipulator, an assembly machine and a punching robot. The machines have floor standing bases. The system was used to manufacture a micro pump module. (Park et al., 2007)

5.2.1.4 Modular Micro and Desktop Factory Concepts

The concepts described in this sub-section are primarily modular microfactory platforms and/or architectures. The main focus of the research is on developing the platform. Development of the machines is usually a secondary goal. Terms such as "modular microfactory" arose with the research. This section introduces eight concepts (see Table 6 and Figure 5).

Table 6. Academic modular microfactory concepts

Year	CC	Concept	Institute	Source
2001	USA	AAA, Agile Assembly Architecture	CMU	Rizzi et al., 2001
2001	GER	AMMS, Advanced Modular Microassembly System / MiniProd	Frauenhofer IPA	Gaugel & Dobler, 2001; Gaugel et al., 2004
2004	FIN	ABAS Desktop Platform	TUT	Lastra, 2004; Jokinen, 2006; Jokinen & Lastra, 2007
2005	CH	Microbox Pocket-Factory	EPFL (LSRO)	Verettas et al., 2005
2005	FIN	TUT Microfactory	TUT	Heikkilä et al., 2007; Heikkilä et al., 2010
2008	JP	Module-Based Microfactory	AMRI & new AIST	Nakano et al., 2008; Ashida et al., 2010
2010	CH	Rotary Assembly Line	EPFL (LSRO)	Kobel & Clavel, 2010
2010	FIN	Desktop Assembly	VTT	VTT, 2010

Figure 5. AAA (Rizzi et al., 2001), AMMS (Gaugel & Dobler., 2001), ABAS (Lastra, 2004), Microbox (Verettas et al., 2005), TUT Microfactory, Module-Based Microfactory (Nakano et al., 2008), Rotary Assembly Line (Kobel & Clavel, 2010), Desktop Assembly (VTT, 2010)

One of the first modular micro assembly concepts was the Agile Assembly Architecture (AAA) developed by Carnegie Mellon University in Pittsburgh USA in 2001. It is a floor standing system and thus slightly larger than normal microfactory concepts. The system is divided into “minifactory” segments, each of which includes a modular base frame, a planar table, precision part feeders and a 3 DOF manipulator overhead. The development started in the mid 1990’s. It was designed for e.g. assembly of magnetic storage devices, small computers and other high-density products. (Rizzi et al., 2001)

One of the first modular desktop-size microfactory concepts was the Advanced Modular Microassembly System (AMMS), developed by Frauenhofer IPA in Germany in 2001. The “plug-and-produce” system is based on a 600x400 mm planar motor table manufactured by L-A-T Suhl AG. Products and/or components are placed on moving carriers, which move with a friction-free air bearing on the planar table. The fixed process modules have dimensions of 100x200 mm, and they are placed next to the planar table, having standardized interfaces. The complete system has dimensions of 800x800 mm. The XY planar stage has a positioning accuracy of 20 µm. The accuracy of the Z axis depends on the used process module. A miniaturized laser diode was used as a case product. It is argued that a wide range of micro products, e.g. mini-encoders, micro-valves or fiber-optics, could be assembled with a similar system. (Gaugel et al., 2004)

An example of Rapidly Reconfigurable Manufacturing Systems (RRMS) is the Actor-Based Assembly Systems (ABAS) developed by Tampere University of Technology (TUT) in Finland in 2004. ABAS is a general agent based architecture to link the available assembly actors to needed assembly operations in a complex manufacturing system. As a pilot, a desktop size intelligent material handling system was constructed. It identifies the optimal route for the pallet, based on the process requirements and the available process stations.

Interfaces of the conveyor modules include power, pneumatics and communication. In addition, it identifies the location of the transport system on the base plate. Such systems are developed for short product life cycles and mass customization. (see Lastra, 2004; Jokinen, 2006; Jokinen & Lastra, 2007)

The first microfactory concept with an integrated cleanroom was the Microbox Pocket-Factory developed by LSRO (a laboratory of EPFL) in Switzerland in 2005. Microboxes have cleanrooms capable of clean class 100 or ISO 5 (i.e. max. one hundred thousand articles of size ≥0.1 µm in a cubic meter). In addition the units include an entry port enabling clean transfer into unit, a 4 DOF scara robot for easy assembly tasks, sensors for process control, a laminar airflow generator and a filtration system. The units have about 1 dm^3 clean working area. Although some prototypes were built, the optimal size of the units was one topic of the research. A "Pocket-Factory" can be constructed out of multiple Microbox units and different feeders. Each unit can conduct one or multiple assembly operations (e.g. gluing, insertion). (Verettas et al., 2005)

The microfactory research at EPFL has continued with another concept, Rotary Assembly Line. It is developed to achieve higher class cleanliness than with linear concept. The circular concept has a central unit including clean air inlet, rotary table for transportation of standard 2 inch trays and interfaces (mechanic, data and power) for the production modules. The production modules around include working area with laminar and horizontal air flow, space for a manipulator, air outlet, as well as inlets and outlets for the components. The modules have dimensions of about 250x250 mm and height of 75 mm. The overall system has a footprint smaller than a square metre. One prototype with two modules is already built. (Kobel & Clavel, 2010; Kobel, 2011)

The TUT Microfactory concept includes an integrated cleanroom as well. The concept is based on small independent microfactory modules (see Figure 5). A TUT Microfactory module has dimensions of 300x200x220 mm and a working space of 180x180x180 mm. All required auxiliary systems are included. The modules are designed to work as a stand-alone unit or as a part of "plug-and-produce" production line. Each module has an individual control unit and standardized interfaces. They can communicate with each other through the physical connections or through WLAN. User interface for a tablet PC has been developed and, with that, one or multiple cells can be controlled using only a single interface device. (Heikkilä et al., 2007)

One of latest microfactory-related projects in Finland is the Desktop Assembly managed by Technical Research Centre of Finland (VTT). Objective of the project was to develop desktop assembly concept for light and small-sized products. As a result, a concept of modular floor standing system was developed. The system includes a smart conveyor system, standardized base modules and specific process modules. The control system is designed to work as a “plug and produce”. (see VTT, 2010; Marstio, 2011; Salmi, 2011)

5.2.1.5 Microfactory Internal Logistics

Two main development directions for desktop size equipment are envisioned: 1) Desktop size equipment can be used next to human operators for helping them by automating a repetitive task; and 2) Desktop size modules can be used to form larger production lines. In both scenarios, the internal logistics of desktop system has to be organized in some way and, because of their size, existing methods from large scale equipment cannot be directly transferred to desktop equipment. From the internal logistic point of view one has to especially consider: 1) the feeding methods of the parts to the production area; 2) the conveying method for the product moving from one cell to the other and; 3) the interfaces between the human operator and the desktop cells. The content of this chapter is originally from (Järvenpää et al. 2010a) and (Järvenpää et al. 2010b).

Feeding methods

Several different feeding methods are available for parts feeding, including tray, tape-and-reel, bowl and machine vision based flexible feeding. Some other, more exotic feeding methods are also researched like sticky or frozen tape and soft tape. Discussions with companies assembling miniaturized products have shown the authors that the most desired methods for feeding are tray feeding and machine vision based flexible feeding. Therefore only these two methods are discussed here.

Tray feeding

Tray feeding is a desirable feeding method for applications in which delicate, fragile or high-quality parts are handled, such as the watch mechanisms. The negative aspect of tray feeding is that it requires the parts to be palletized on trays beforehand. Palletizing is a non-value-adding activity and is often manual. The trays also need a lot of space, both in the storage and on the assembly line. Tray feeding requires a tray changer mechanism, which removes the empty trays from the microfactory module and then fills the tray fixture with full one. Another option is to feed the trays manually by a human operator. A conceptual idea of the tray changer system can be seen in Figure 6. This kind of changer mechanism also needs a lot of space and increases the size of the overall system.

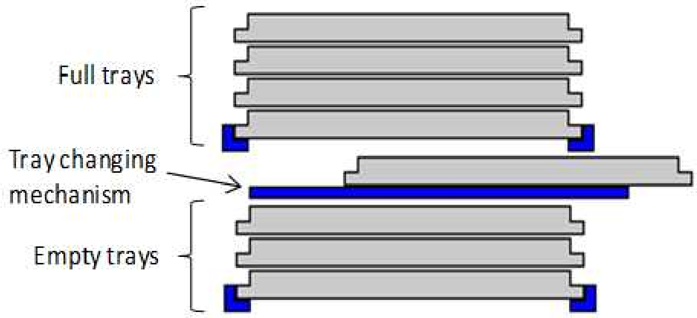

Figure 6. Tray changer concept (Järvenpää et al. 2010a).

In order to increase the flexibility of the feeding and handling system all trays should have similar handling, positioning and locking interfaces. In order to keep the amount of trays reasonable, generic trays should be used instead of dedicated ones. Generic trays do not have part specific caves for the parts and their main aim is just to keep individual parts apart from each other. They allow different, but similar size, parts to be fed with the same tray. Generic trays, however, require more intelligence from the picking robot, because it has to be able to recognize the exact position and orientation of the part before picking. This adaptivity and intelligence is usually implemented with machine vision systems.

Flexible feeding

For components without critical surface quality a machine vision based flexible feeding is a more desirable method, because the parts can be fed directly as bulk to the assembly cells without palletizing or pre-orientation. The working principle of flexible feeders is based on using a machine vision system, which recognizes the part and allows the position and orientation to be calculated from the image of the system. All the parts are not suitable to be fed by this kind of machine vision based feeder. The shape and appearance of the component has to fulfil certain requirements. First of all it needs to contain geometrical features which allow it to be directed into a specific area in the feeder for picking. The features should also be recognizable by the machine vision to allow the detection of the component itself and its position and orientation unambiguously. As a penalty of part misorientation, the cycle time for picking is often longer.

Conveying methods

In line type production, especially assembly, the product moves from one station to the next one. Depending on the application the product may either be placed freely on a flat conveyor belt, which moves the product through the stations, or if pre-positioning is required the product is attached to a product specific carrier or jig, which moves along the conveyor. Third option is to transfer the product from one desktop cell to the next one by a small manipulator.

In TUT a concept of a carrier system for product has been designed, presented in Figure 7. Jigs or inserts are product specific, but the carriers are the same for different products. This enables standardised features like stopping, locking, orientation and positioning, and identification of the carriers and also the products on the carrier. This supports the reuse of the carriers and allows the same transportation modules to be used for all products and product variants. The carrier system concept enables the product to be removed easily from the production line for manual operations. The carrier system contains also an escort memory, such as RFID, which allows keeping track on the location of the carrier and the operations that have been performed for the product.

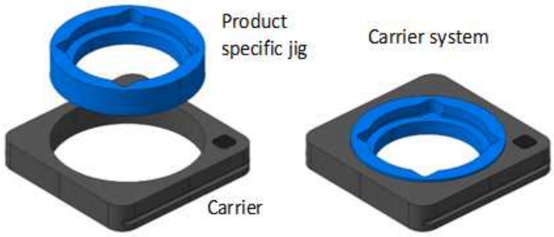

Figure 7. Carrier system for the base part (Järvenpää et al. 2010a).

There are multiple different conveying methods that can be used to handle the factory level logistics, meaning to transport the product through all the required process steps on the production line. A modular belt conveyor with standardised interfaces can be integrated e.g. in the TUT-microfactory modules. This ensures the flexibility and reconfigurability of the line. Figure 8 illustrates an example of a microfactory system for a specific assembly process chain with belt conveyor modules passing through the microfactory process modules.

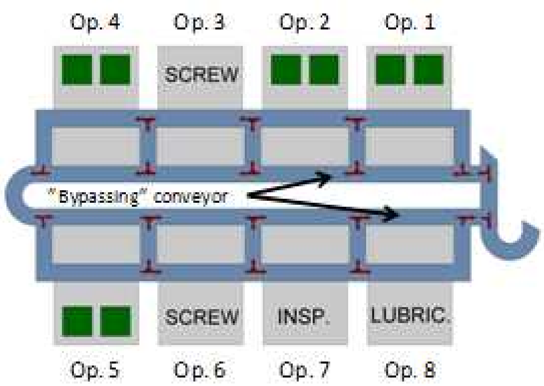

Figure 8. Example of a station based microfactory system and integrated assembly process chain (Järvenpää et al. 2010b).

The most important thing in the material logistics regarding the reactivity of the line is that the carriers can be freely routed to any cell. This is especially important in case of duplication of bottleneck process or in case of failures in the system, e.g. if one process module breaks down, and other modules can provide the same process step. Because of modular construction, the process module can be exchanged on-the-fly while the carrier is routed to other process unit capable of performing the same step. For the re-routing purposes there is a "bypassing" conveyor, which allows the carriers to skip some process modules. Figure 9 presents an example of a factory level assembly system layout with the belt conveyor going through all the microfactory modules and lines. The assembly factory is divided into lines or clusters of modules, which all perform one assembly in the process chain. Example of this kind of cluster is shown in Figure 8. This kind of division supports easier management of the overall system consisting of vast amount of assembly steps. One benefit compared to traditional macro-size systems is that human can see with “one sight” bigger part of the factory and process chain, making the process easier to manage and understand.

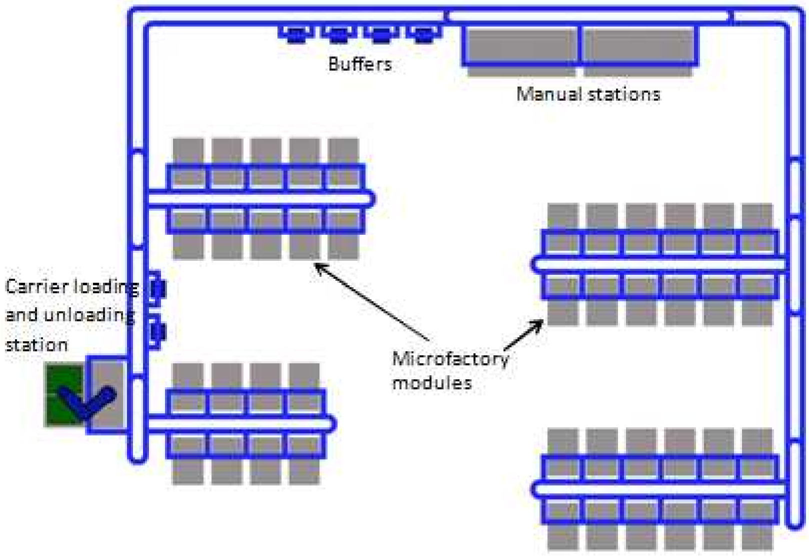

Figure 9. Example of an integrated micro assembly factory (Järvenpää et al. 2010b).

Interface between desktop modules and human operator

In today’s sustainable manufacturing paradigm the goal is not to replace humans with full automation, but to keep the human in the loop and to support the human workers in their work by performing specific tasks automatically. These could be the boring, repetitive and stressing tasks; hazardous tasks; or tasks with high precision or high quality demands. The human–machine interface must be optimized in order to maximize the benefits of both human skills and machine capabilities. Therefore the operations that need special skills should be performed by humans and difficult tasks (because of small part size or high accuracy or quality requirements) or boring repetitive tasks (such as component palletizing) by automated desktop units.

Especially some quality control activities are difficult to automatize and needs to remain manual. Therefore the interface between the desktop modules and manual stations presents an important topic. The manual stations have to be compatible with the desktop system not only from their physical interfaces, but also considering the control on the factory level. Because the material logistics from one desktop module to another is automatic, flexible use of the manual stations requires them to be integrated into the same material logistics system together with the desktop modules. In Figure 9, similar belt conveyors move the carriers through microfactory units and the manual stations. The manual stations have to also contain the

RFID-readers (or other similar techniques) in order to keep on track which operations have already been accomplished for the product.

The carrier system concept presented earlier aims to simplify the interface between the automatic and manual working modes. This kind of carrier system allows the product to be removed from the microfactory line for manual operations, either when the next operation is too complex for automation or when failures have occurred and human operator needs to make inspection and corrections for the product.

5.2.1.6 Energy Efficiency of Microfactories

Energy saving is one often cited advantage of microfactories. For example, Kawahara et. al. (1997) estimates that downscaling equipment to size 1/X reduces consumed energy by factors presented in Table 7. In that table, Kawahara et. al. separated energy consumption to three categories: 1) Operating energy, which is proportional to the moving 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 (cutting, grinding). As can be seen from Table 7, majority of the energy used is needed for illumination and air conditioning and these also have the largest potential for energy savings. On the other hand, according to Table 7, the needed processing energy would not decrease at all.

Table 7. Average energy consumption in actual factories and Energy saving effect when the factories are miniaturized to 1/X (Kawahara et. al., 1997)

	average consumption in actual factories [%]	energy-saving effect (1/X miniaturization)
operating energy	13	$1/X^3$
environmental energy		
illuminating	23	$1/(1.5 \times X^3)$
air-conditioning	56	$1/(3 \times X^3)$
processing energy and others	8	1

A real world example of reduced power consumption can be found from Escribano Gimeno (2010). In her study, she measured average electrical power consumption of five different machines while they were in different states (see Figure 11). Figure 10 shows the machines which were: Hisac 500 OF assembly cell, Stäubli RX60 robot (with Adept controller), Mitsubishi RP-1AH, prototype Schunk desktop scara robot, and prototype of current Asyril Pocket Delta robot. First two machines (Hisac and Stäubli) are "conventional size" machines, Mitsubishi and Schunk are small enough to be placed on desktop and Pocket Delta can be integrated to 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).

Figure 10. Machines used for power consumption measurements, from upper left corner: Hisac 500 OF, Stäubli RX60, Mitsubishi RP-1AH, Schunk desktop scara (prototype), Pocket Delta (prototype). Images are not in same scale. (images from Escribano Gimeno, 2010)

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 11 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 12. 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).

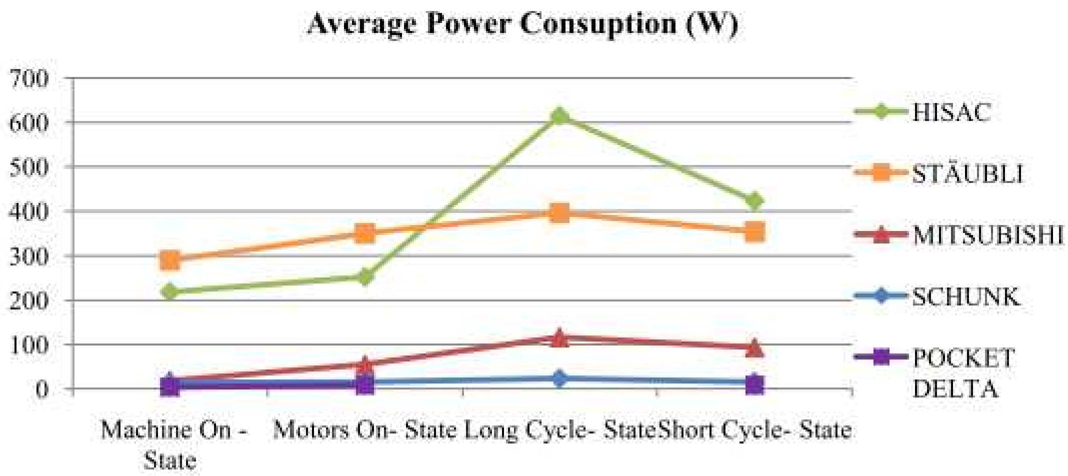

Figure 11. Average power consumption while machines were in different states. Pocket Delta could not perform the long cycle (Escribano Gimeno, 2010)

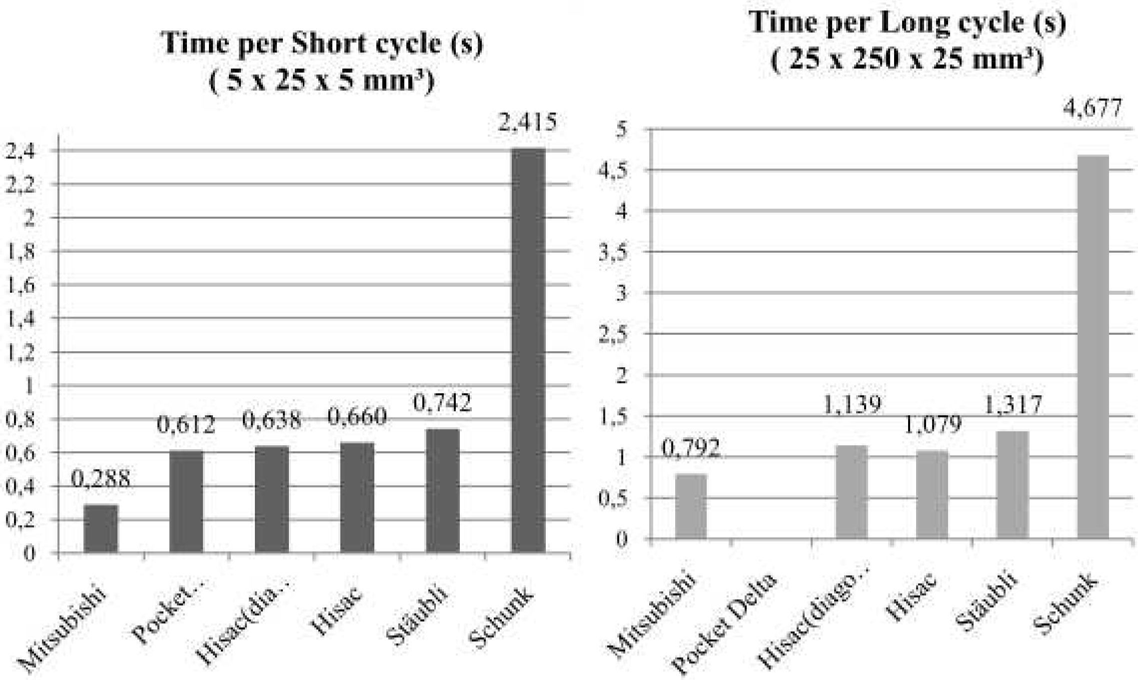

Figure 12. Work cycle durations. Hisac Diagonal refers to situation where Hisac performed the horizontal movement using both X and Y axis. Otherwise machines made horizontal movements only in X or Y direction, depending on the machine. (Escribano Gimeno, 2010)

To conclude, Escribano Gimeno's (2010) measurements do not directly support Kawahara's (Kawahara et. al., 1997) estimations about the amount of energy saved. However, they do indicate that there is great potential for operating energy savings and possibly even greater savings in, for example, air conditioning.

5.2.2 Commercial Micro and Desktop Factory Solutions

Even though micro and desktop factories have been under research for several years, large industrial breakthrough still remains unseen. However, there are several individual industrial examples ranging from micro and desktop production systems to commercial desktop size 3D printers to small size hobby and educational machining units and 3D printers.

At the moment, it appears that miniaturized machining units have the largest coverage and also desktop-size stand-alone automation units have been developed for multiple purposes. Furthermore, desktop-size 3D printers and rapid prototyping units are appearing on the market as well. Instead, only a few modular desktop factories have been developed. This section presents examples of different types of commercial desktop-size equipment. This section is mainly origin from the Master of Science thesis of Anssi Nurmi (2012).

5.2.2.1 Commercial Miniaturized Machining Units

Since the millennium, multiple commercial small-size and stand-alone machining units have been developed (see Table 8 and Figure 13). For example, Japanese NANO Corporation published the Micro Turning System in 2002. The suitcase-style system has a base of 150x100 mm and it includes a CNC precision lathe (Iijima, 2002). According to the authors' knowledge, it has been one of the only commercial factory-in-a-suitcases. The miniature machining systems are designed for versatile materials and applications, e.g. metal (micro mechanics, jewellery and watches), glass (micro-optics), plastic (hearing aids), ceramics (dental) and biodegradables (implants).

Table 8. Examples of commercial small-size stand-alone machining units

Year	CC	Machine	Company	Source
2002	JP	Nanowave MTS2	Nano Corporation	Iijima, 2002; Nano Co., 2005a
2003	JP	Multi-Pro	Takashima Sangyo Co.	see Endo, 2010; Takashima Sangyo, 2011
2003	JP	Multi-function Turning Center	DTF	see DTF, 2011
2004	JP	TRIDER-X	Rinken Co.	Lin et al., 2004
2004	JP	Desktop Milling Machine	PMT Co.	see Okazaki et al., 2004
2004	JP	Cylindrical cells	SII Co.	see Okazaki et al., 2004
2005	JP	Nanowave MTS3 Nanowave MTS4 Nanowave MTS5/MTS6	Nano Corporation	Nano Co., 2005b Nano Co., 2005c Nano Co., 2005d
2008	USA	G4-ULTRA CNC	Atometric Inc.	Atometric Inc., 2008
2008	USA	Microlution 363-S	Microlution Inc.	Microlution Inc., 2007
2008	USA	EM203 GM703	SmalTec	SmalTec, 2008a SmalTec, 2008b
2009	USA	MM903	SmalTec	SmalTec, 2009
2009	JP	Micro mill CVN-2000	Enomoto Kogyo	Enomoto Kogyo, 2009
2010	GER	Impression line: cam4-02, cam5-02, cam4-K1, cam4-K2	vhf camfacture AG	vhf camfacture, 2010
2011	FIN	Kolibri	Wegera	Wegera, 2011a

Figure 13. Micro Turning System (Iijima, 2002), CAM 4-02 (VHF camfacture, 2011), Kolibri (Wegera, 2011b)

Besides the industrial machines, some inexpensive and low-precision desktop machines have designed for hobby and educational use (see Table 9 and Figure 14). The iModela iM-01 is an affordable 3D hobby mill designed by Roland DG Corporation. The system has dimensions of 214x200x205 mm and it weighs 1.7 kg. The cells folds up and it can be packed in a suitcase. (Rolanda DG Co., 2011a) The prices vary between $500 and $5000. A Japanese company Originalmind has multiple low-priced machining units, e.g. the BLACKII 1510. It is an educational CNC machine with a base 150x100 mm and a weight of 8.3 kg. Prices start from $1279. (Originalmind, 2011)

Table 9. Examples of commercial small-size hobby and educational machining units

Year	CC	Machine	Company	Source
Since 1999	USA	CNC tools for hobbyists	HobbyCNC	HobbyCNC, 2011
2009	AT	Emco Concept Mill / Turn (Used in integration with e.g. Festo Didactic training system)	EMCO group	Emco, 2012
2010	UK	E.g. PRO II MDX-540 and RotoCAMM MDX-40AE	Techsoft UK	TechSoft UK, 2010a TechSoft UK, 2010b
2011	JP	iModeal iM-01	Roland DG Corporation	Rolanda DG Co., 2011a; Rolanda DG Co., 2011b
2011	JP	Low-priced machining units, e.g. BLACKII 1510	Originalmind	Orginalmind, 2011

Figure 14. iModela iM-01 (Rolanda DG, 2011b), RotoCAMM MDX-40AE (Techsoft UK, 2010), BLACKII 1510 (Originalmind, 2011)

In addition, some companies are specialized only in educational machines, e.g. a British company Techsoft UK. They have, for example, models PRO II MDX-540E and RotoCAMM MDX-40AE, which are 3/4-axis educational CNC machines. The latter is slightly heavier and larger (1060x1100x978 mm, 170 kg) but they both can be placed on a table. The prices start from $4695 and $13995. (Techsoft UK, 2010a, 2010b)

In addition, there are some construction-kit type CNC machines on the market, provided by e.g. American HobbyCNC. The kits start from $550 and the machines are usually built out of plywood or plastic. (HobbyCNC, 2011)

5.2.2.2 Commercial Small-Size Stand-Alone Robotic, Assembly and Process Cells

Some commercial small-size and stand-alone production cells have been developed. The machines are divided here into process (see Table 10 and Figure 15) and robotic cells (see Table 11 and Figure 16). In 2005, the Japanese Desktop Factory Consortium developed the Ultra Compact Hot Embossing Machine and the Desktop Nickel Plating Machine. The former is a floor standing machine and the latter is a desktop-size unit with dimension of 812×303×300 mm. (see DTF, 2011)

Table 10. Examples of commercialized small-size stand-alone process cells

Year	**CC**	**Product**	**Company**	**Source**
2005	JP	Ultra Compact Hot Embossing Machine	DTF	see DTF, 2011
2005	JP	Desktop Nickel Plating Machine	DTF	see DTF, 2011
2007	UK	DS2TM and DSXTM (laboratory/diagnostics automation)	DYNEX Technologies	DYNEX Technologies, 2007a DYNEX Technologies, 2007b
2009	IT	Global240 and Keylab (laboratory/chemistry automation)	BPC BioSede SRL	BPC BioSede SRL, 2009a BPC BioSede SRL, 2009b
2010	USA	Sesame (molding)	Medical Murray	Medical Murray, 2011

Figure 15. Ultra Compact Hot Embossing Machine (see DTF, 2011), Desktop Nickel Plating Machine (ibid.), Nanomolding machine Sesame (Medical Murray, 2011)

Medical Murray is a medical device engineering and manufacturing company form USA. In 2010, they published a nanomolding machine called Sesame. The machine is a floor standing, but relatively small when compared to other similar molding machines. With the machine, materials such as bioabsorbable polymers, as well as thermoplastic and silicone rubber materials can be moulded. Applications include e.g. overmolded polymers, electronics or radiopaque markers. (Medical Murray, 2011)

In addition, multiple miniaturized automated laboratory devices have been developed, e.g. analysis systems (DYNEX Technologies, 2007a, 2007b) and chemistry analysers (BPC BioSede SRL, 2009a, 2009b).

In addition, small-size and stand-alone robotic cells have been developed for specific applications. In 2009, Swiss company Asyril published their first table top cell, Asyfeed Pocket. The overall size of the cell is 400x400x500 mm. It is a miniaturized version of the floor standing cell, Asyfeed Desktop (800x800x2250 mm). The both include a PocketDelta Robot (highly miniaturized and high precision delta robot), an Asycube (flexible feeding system) and an Asyview (vision system). They are primary designed for sorting and palletizing of bulky micro-components. Work-cycles up to 3 components per second can be achieved. In addition, the cells can be modified to assembly and measurement tasks. (Asyril, 2010) In 2011, an improved version of Asyfeed Pocket was published. (Asyril, 2011a)

Table 11. Examples of commercialized small-size stand-alone robotic cells

Year	CC	Product	Company	Source
2009 - 2011	CH	Asyfeed Pocket	Asyril	see Asyril, 2010, Asyril 2011a
2010	FIN	J505-62	JOT Automation	JOT Automation, 2010a
2011	FIN	Roboline	Biohit Oyj	Biohit, 2011a

Figure 16. Asyfeed Pocket 2009 (Asyril, 2010), J505-62 (JOT Automation, 2010a), Roboline (Biohit, 2011a), Asyfeed Pocket 2011 (Asyril, 2011a)

Similarly, JOT Automation has developed the J505-62 Desktop Robot Cell for Screw Insertion. The cell has dimensions of 495x754x962 mm, and it includes e.g. linear motor driven X and Y axes, two screwdrivers and a four index rotary table. Compatibility to JOT Automation's Lean production lines is also mentioned. (JOT Automation, 2010a)

Secondly, some desktop-size robotic cells are developed for specific non-manufacturing applications. Good examples are the medical and bio industries. Biohit is a Finnish company, specialized in liquid handling products, i.e. electronic and mechanical pipettes and disposable pipette tips. In 2011, Biohit launched the Roboline, a desktop cell for automated pipetting. The unit has a size of 347x346x381 mm and it weighs 11.5 kg (Biohit, 2011a). (Later the Biohit has been acquired Sartorius Biohit)

5.2.2.3 Commercial Micro and Desktop Factory Cells

One of the first commercial microfactory units was the Desktop Factory® developed by NIKED Sankyo (former Sankyo Seiki) (see Table 12 and Figure 17). The modules are 170 mm wide and they are designed for multiple purposes, e.g. cleaning, coating, screwing, measuring and assembly. (Tuneda, 2005) Another famous Japanese microfactory unit is the Multi-Pro developed by Takashima Sangyo. Multi-Pro is a versatile 3-axis desktop machine platform. The dimensions of the system are 476x477x625 mm. Besides the designing and manufacturing of the machinery and equipment, Takashima Sangyo manufacturing precision machined parts. They have already more than 300 miniaturized machines in use. Multiple processes, e.g. laser machining, precision processing and jig grinding, have been miniaturized. (see Endo, 2010; Takashima Sangyo, 2011)

Table 12. Examples of commercial multifunction micro and desktop factories

Year	CC	Product	Company	Source
2003	JP	Desktop Factory DTF®	NIDEK Sankyo Co.	see Tuneda, 2005
2003	JP	Multi-Pro	Takashima Sangyo Co.	see Endo, 2010; Takashima Sangyo, 2011

2004	USA	Nexar® and Araya® (laboratory automation)	Douglas Scientific	Douglas Scientific, 2012
2007	GER	Lean Desktop Factory	Bosch Rexroth AG	Klemd, 2007
2009	GER	LabFab (laboratory automation)	Festo AG & Co.	Festo, 2011
2010	FIN	MAG Lean	MAG Oy	MAG, 2010
2011	GER	microFLEX	IEF Werner GmbH	Hofmann et al., 2011; IEF Werner GmBH, 2011
2011	FIN	JOT Lean	JOT Automation	JOT Automation, 2011

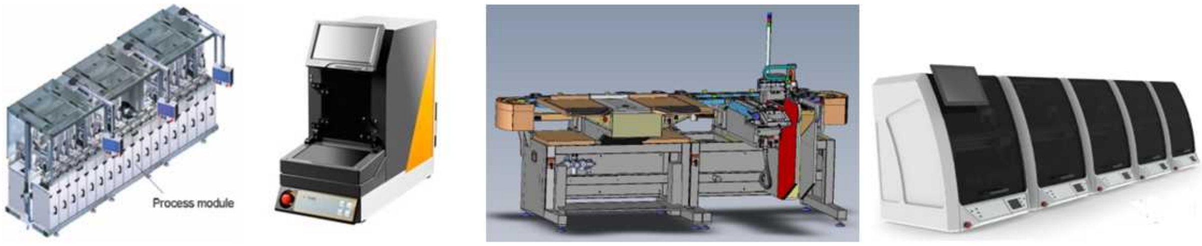

Figure 17. Bosch Lean Desktop Factory (Klemd, 2007), MAG Lean (MAG, 2010), microFLEX (Hofmann et al., 2011), JOT Lean (JOT Automation, 2011)

In Europe, one of the first “Desktop Factories” was developed by German Bosch Rexroth AG. Despite the name, it is a modular floor standing system. However, the width of the modules is only 220 mm. As a result, a 30 m long automated assembly line can be squeezed down to 4.5 m (Klemd, 2007). In 2010, a Finnish automation provider, Master Automation Group, introduced MAG Lean cells. In contrary to Bosch modules, MAG Lean is truly a desktop-size system. The dimensions of the 3-4 axis cells are 250x500x500 mm and they weigh only between 25 kg and 40 kg, depending on the configuration. Applications include e.g. pick and place, screw inserting, testing and laser marking of aluminium, steel and plastic components. (MAG, 2010) In 2011, Master Automation Group merged together with another Finnish automation provider, JOT Automation. The recently published JOT Lean cell includes two sizes, 533x600x710 mm and 333x600x710 mm. It is an improved version of the previous MAG Lean generation in all ways. Plasma treatment has been stated as a potential application as well. (JOT Automation, 2011)

In Germany, another floor standing system, microFLEX was developed by IEF Werner GmBH in cooperation with KIT. The system is based on 1200x800x800 mm modules, including 800x1000 mm space for processes and in/out buffers. The logistics system is based on 80 mm standard trays and RFID tags. It is designed for different levels of automation (from manual to semi-automatic and full automation). The module size corresponds to manual assembly tables in the industry the system was designed for. (Hofmann et. al., 2011; Hofmann, 2011)

At field of laboratory automation, Nexar® and Araya® from Douglas Scientific are a modular concept for inline liquid handling to support high throughput processing of sub-microliter volumes and analysis. The Araya® is a fluorescence scanning analyser. Their solution bases on Well Array Tape™ compatible with standard 96- or 384-well plate, which is processed from reel at the inline system. In the end tape is sealed before rolling into end reel.

Festo has presented around 2009 a concept called LabFab (Festo, 2011), which targets establishing a generic and modular platform for laboratory automation, with plug and produce capabilities presented in modules. It bases on planar motor transporting the product or samples (e.g. well plate) from process station to another. This concept originates from the Advanced Modular Microassembly System (AMMS) or MiniProd concept researched and developed by FhG-IPA (Gaugel et al., 2004).

5.2.2.4 Commercial Desktop-Size 3D Printers and Rapid Prototyping Units

In general, 3D printers can be used to e.g. proofing a concept, testing functionality of parts or demonstrating products for a customer. Recently 3D printers have started to shrink to a desktop-size as well (see Table 13 and Figure 18). Some well-known models include Dimension uPrint and uPrint plus (Dimension, 2010), Solido SD300 Pro (Solido LTD, 2009), 3D Systems V-Flash (3D Systems Inc., 2011b), Objet24 (Objet, 2010a) and Objet30 (Objet, 2010b). Weights of the printers vary between 45 kg and 93 kg, dimensions between 160x210x135 mm and 660x685x787 mm and costs between $10,000 and $40,000. The layer thickness varies between 0.028 mm and 0.254 mm. An American company Desktop Factory has been developing an inexpensive desktop-size 3D printer, Desktop Factory 125ci. The printer has dimensions of 508x635x508 mm and it weighs 50 kg. The layer thickness is 0.254 mm. Prices start from $4,995. (3D Systems Inc., 2011a) However, the product has not been launched yet.

Table 13. Commercial small-size 3D printers and rapid prototyping units

Year	CC	3D printer	Company	Source
2009	USA	uPrint and uPrint plus	Dimension (Stratasys)	Dimension, 2010
2009	IL	SD300 Pro	Solido	Solido LTD, 2009
2009	USA	V-Flash	3D Systems	3D Systems Inc., 2011b
2010	USA	ModelMaker	2BOT physical Modeling Technologies	2BOT physical Modeling Technologies, 2010
2010	USA	Objet24 Objet30	Objet	Objet, 2010a Objet, 2010b

2011	USA	Objet260 Connex	Objet	Objet, 2011
2012	USA	Desktop Factory 125ci	Desktop Factory	3D Systems Inc., 2011a

Figure 18. ModelMaker (2BOT physical Modeling Technologies, 2010), Objet260 Connex (Objet, 2011), Desktop Factory 125ci (3D Systems Inc, 2011a)

Some 3D printers can print parts from multiple materials. One of the smallest devices is the Objet260. The device can print up to 14 different materials into a single printed part. Over 60 materials are available. In addition, the device has eight printing heads and accuracy up to 16 µm (depending on the material used). The printer is slightly larger, having dimensions of 870x735x1200 mm and a weight of 264 kg. (Objet, 2011) It is a bit over desktop-size but it does fit into in a corner of an office.

Besides additive 3D printers, other rapid prototyping units exist as well. For example, an American company 2Bot has developed a subtraction-based rapid prototyping device, ModelMakerTM. The unit has a cutter head and the models are made from high density foam. It is designed especially for educational use and prototyping. The dimensions of the unit are 635x635x330 mm and the device can be plugged into a computer via USB. (2BOT physical Modeling Technologies, 2010) Although material subtraction method places some restrictions for shapes, impressive prototypes have been created with the machine. It could be useful especially for landscape architects.

Similarly to the machining units, some inexpensive and low-precision 3D printers have been designed for hobby and educational use as well (see Table 14 and Figure 19). Both commercial products and open source based do-it-yourself machines exist. The first open source 3D printer project was the RepRap, based on University of Bath in UK. It is a truly communal project. So far, five models have been developed: RepRap 0.2 (in 2006), Darwin (in 2008), Mendel (in 2009), Huxley (in 2010) and Prusa Mendel (in 2010). All the designs are open source; anybody can further develop them and publish them online. One goal is that 3D printer could print the parts for building another 3D printer i.e. replicate itself. One can either download the designs and print the parts itself or buy the parts from other members of the community. Price of a complete system varies between $400 and $650. All the models are desktop-size and lightweight. (RepRap, 2011) Another community based project is the Fab@Home. They are more expensive and more accurate than the RepRap printers. The material is injected with two components. (Fab@Home, 2010, 2011).

Table 14. Examples of commercial desktop-size hobby and educational 3D printers

Year	CC	3D printer	Company	Source
2006-2010	UK	RepRap 0.2, Darvin, Mendel, Huxley and Prusa Mendel	RepRap (community project)	RepRap, 2011
2006, 2010	USA	Model 1 and Model 2	Fab@Home (community project)	Fab@Home, 2010 Fab@Home, 2011
2009, 2010	USA	CupCace CNC (past) and Thing-O-Matic CNC	MakerBot	MakerBot, 2011
2009-2011	UK	RapMan 3.1 (past) and 3DTouch, RapMan 3.2	Bits from Bytes	Bits From Bytes, 2011

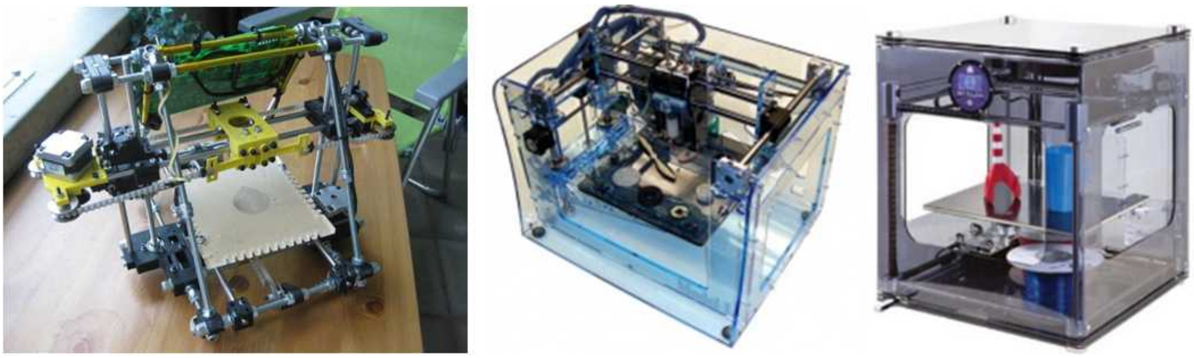

Figure 19. RepRap Huxley (RepRap, 2011), Fab@Home Model 2 (Fab@Home, 2011), 3D Touch (Bits from Bytes, 2011)

Companies providing inexpensive 3D printers include e.g. MakerBot from Broklyn and Bits from Bytes from UK. MakerBot have had two models; CupCace CNC and Thing-O-Matic CNC. They are made out of plywood. CupCace CNC started from $649, but it is not on sale anymore. The price of Thing-O-Matic CNC varies between $1299 and 2500. (MakerBot, 2011). The printers of Bits from Bytes base on RepRap designs. Currently they have two models, RapMan 3.1 and 3DTouch. The former is a construction kit and the latter is a ready-made printer. Prices vary between $494 and $4015. (Bits from Bytes, 2011)

5.2.3 Gap between Research and Commercial Products

There is still a notable gap between the research and commercial solutions. The biggest challenges with the commercialization of the research solutions can be listed as follows:

- The reliability of the research equipment
    - The reliability of the research equipment may not be good enough for the real industrial production. Usually the research solutions are not built with the

objective of continuous operations and therefore the reliability is not the most important development objective.

- Exploitability of the research equipment in a commercial sense
  - The solutions used in research equipment may not be enough cost efficient for commercialization.
- Ease of the operation
  - In the research, the main interest is usually on the process or mechatronic device whereas the development of the control and software is often just a necessary action that needs to be done. Therefore the usability or software architecture/implementation issues are seldom within the scope of the research. In many cases this should be acceptable approach.
  - The ease of operation and usability of the microfactory devices should be improved, especially when it comes to special issues relating to microfactories. These are characterised by the small components to handle and process; operator accessibility to the process; and new ways to interact with devices and process.
  - Also ease of service and maintenance operations should be improved. Since research equipment is often not designed for continuous use, these aspects are easily neglected.
  - Ease of reconfiguration both on hardware and software level is lacking both on research and industrial sides.
- Size of the equipment
  - The microfactory solutions developed by academic world, e.g. TUT microfactory concept, are often too small for cost optimised industrial applications. The research done in universities and research centres is, by nature, usually not targeted for commercialization, but for publishable scientific results. Therefore the commercialization of microfactory solutions has been lagging behind.
- Degree of Integration
  - The research is often focusing on proving a single aspect (e.g. that a certain process is feasible and functions at microfactory size) and it needs to be done with limited resources. Therefore the integration and comprehensive view is not the primary objective.
- The actual needs of the industry are not known
  - The research actors are often lacking deep knowledge about what are the current industrial requirements and needs. Do the requirements relate to components, concepts and architectures, process development, and/or new products? Or something else?

5.3 Small-Size Components and Supporting Technologies

The significant proportion of the price of the manufacturing machinery originates firstly from the labour costs in the design and manufacturing (especially in the Western countries), and secondly from the components used for building up the device. It is therefore important to identify the price optimum for the components. The hypothesis is that when the size (volume) of the component either decreases or increases the price will increase (see Figure 20) and thus setting the price optimum for desktop machines. Another hypothesis relates to the correlation between accuracy and price. Increase of accuracy will increase the price. It is foreseen that the general trend of size reduction will also push the optimum further down in size.

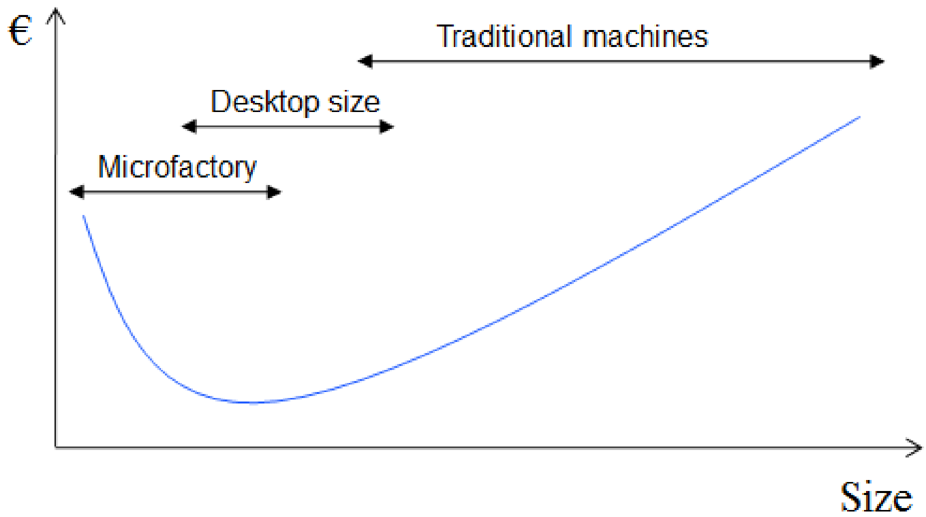

Figure 20. Price vs. Size comparison. Lower is better

Another aspect can be expected from performance and size relation (see Figure 21). It is often the case that microfactory class devices are slow and less accurate especially when considering the relative accuracy. For the absolute accuracy the situation can be the opposite.

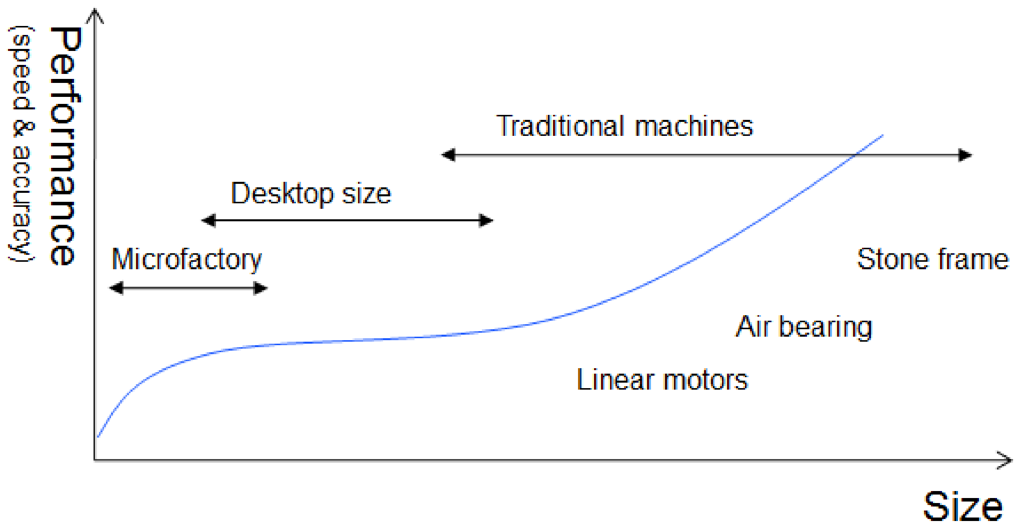

Figure 21. Performance (speed and accuracy) vs. Size comparison. Higher is better.

One of the benefits for using smaller machines is better correspondence of currently needed and currently available production capacity. The small and inexpensive machines, which preferably are modular and reconfigurable, can be utilised in agile and responsive ways to closely match the current demand. In contrast, traditional or large machines with high capacity show large investment and capacity steps (see Figure 22). It is obvious that there is high overcapacity and risk of not utilised investment, especially when the future needs are often unknown.

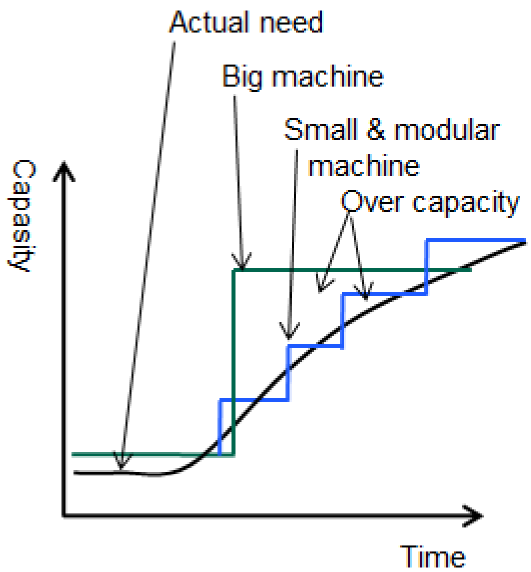

Figure 22. Correspondence of capacity to demand when using different size equipment.

In order to verify the previous hypothesis, some component pricing and performance indicator data is collected and information analysed. The prices of components are list prices for small quantities (1 to 5). The actual acquiring price for a company is regulated much by the order quantity, delivery costs, and company-to-company policies and relationships. It is to be noted that some other issues other than the size and accuracy may affect the component's price as well, which are not visible on the survey. Such things could be e.g. large production volume of certain models, which lowers the price of specific component; or technology used in the product/production. Vice versa some very low sales volume models may have larger price within the pricing of the supplier company. These variables are out of the reach of this study.

5.3.1 DC Motors

Analysis of high end and precision DC motors includes four suppliers and 161 motors of which 66 are brushless and 95 DC motors with brushes. Size range of motors is from 4 to 90 mm.

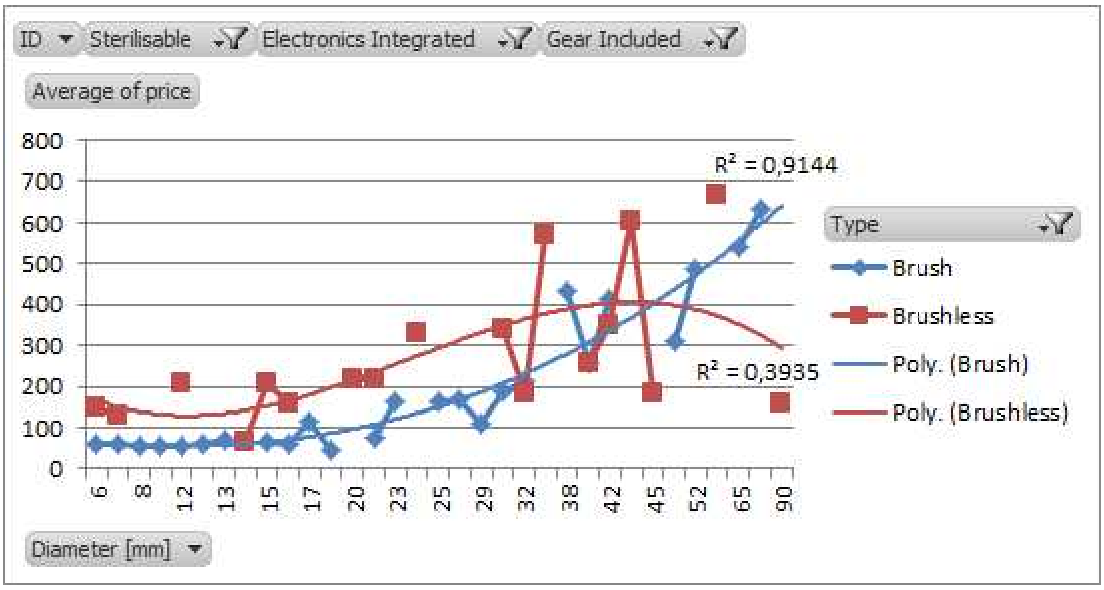

Figure 23. Price (EUR) vs. Size comparison. Lower is better.

Analysis excludes sterilisable motors and motors with integrated gear and/or electronics, because those increase the price relatively more than the size. From Figure 23 can be concluded that brushless DC motors are generally more expensive than the brushed ones and the larger size motors are costing more. The same trend of increasing prices seems to appear also for very tiny motors (Diameter < 10 mm). Variations of prices between the brushed DC motors from different vendors are smaller and the trend is more accurate. This can be recognised from the fitted curve, which has 91% fit. Price optimum for brushless motors lies at range of 8..22 mm. Optimum for brushed motors is around 8..32 mm.

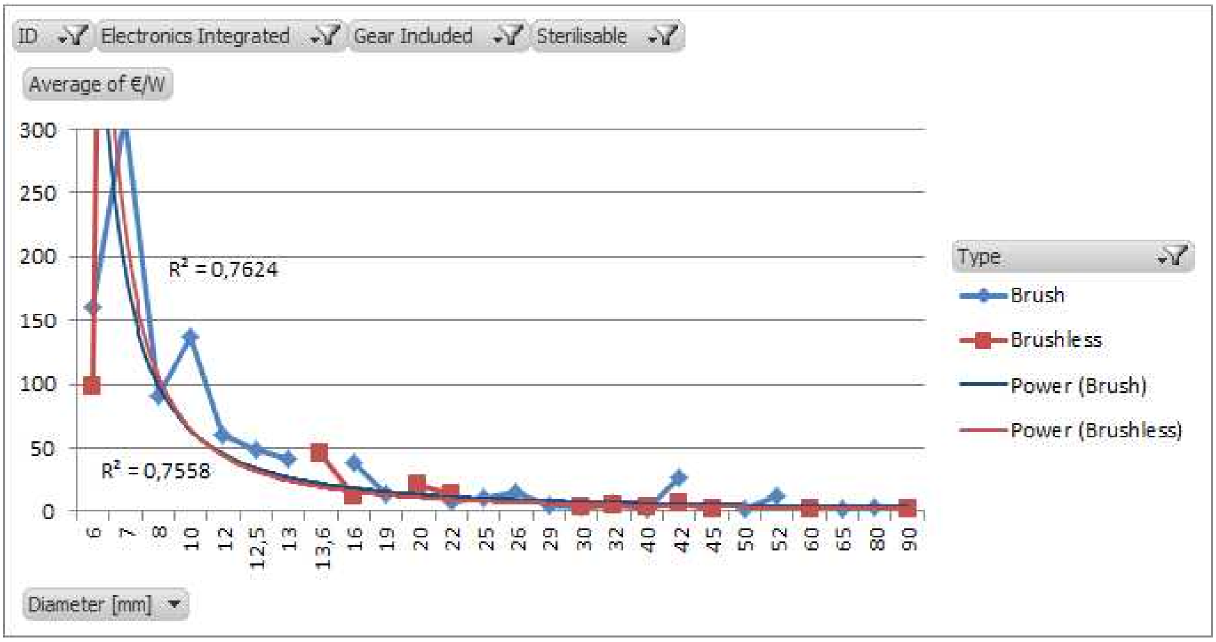

Figure 24. Price (EUR) per power vs. Size. Lower is better.

The trend lines of price per power show that both brush and brushless motors follow same trends quite identically (Figure 24). A conclusion can be also made that with tiny motors the cost of a single watt (power) is increasing very rapidly as a function of size. The price of the power is quite flat after the sizes larger than 16 mm and has no large cost differences. Again, analysis excludes sterilisable motors and motors with integrated gear and/or electronics.

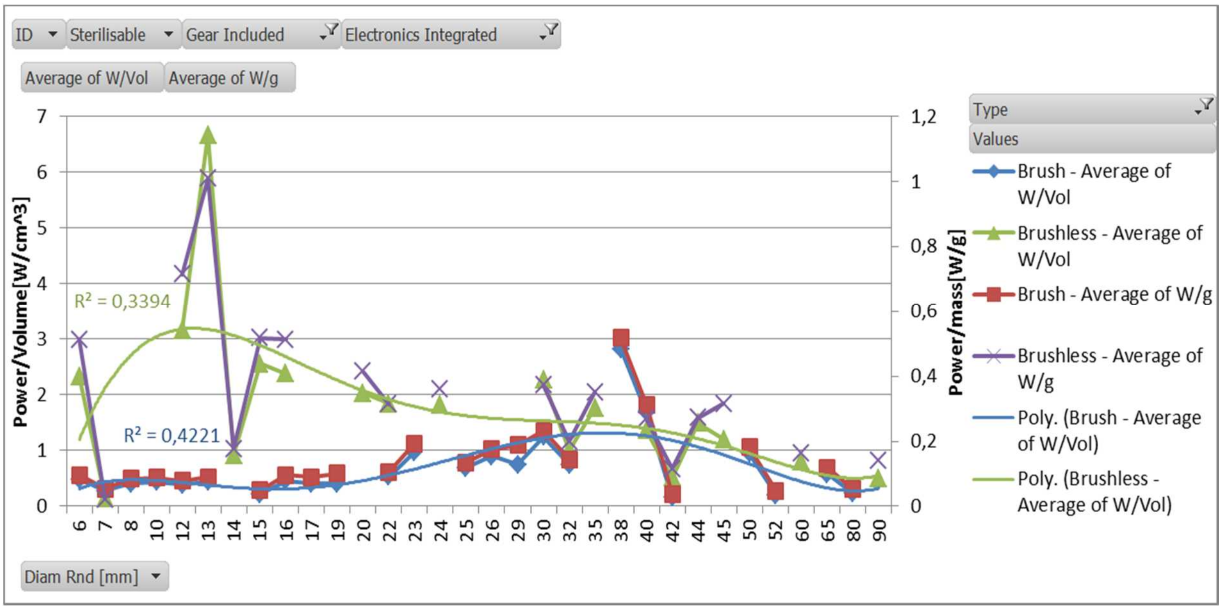

Figure 25. Power density vs. size. Higher is better.

Whether comparing either the volume or mass power density, both seem to be following the same trends at both DC motor technologies (Figure 25). Therefore the trend lines are drawn only for the volume based power density. Brushless DC motors have generally better power density ratio than the brushed motors, especially at smaller motor sizes. Optimum for brushless motors seems to be in the size range of 12..25 mm. The power density of brushed DC motors fluctuates less over the different sizes. Though some kind of optimum can be found at range of 25..50 mm, where brushed motors are in same or even higher than the brushless motors. However, the variation between different vendors is large and can be recognised at the graph from the zig-zag pattern. In some cases vendor A has models for size of e.g. 30 and vendor B only for 32 and therefore the averaged data is not necessarily available for all sizes. Motors with integrated gear and/or control electronics are excluded. Sterilisable ones are included.

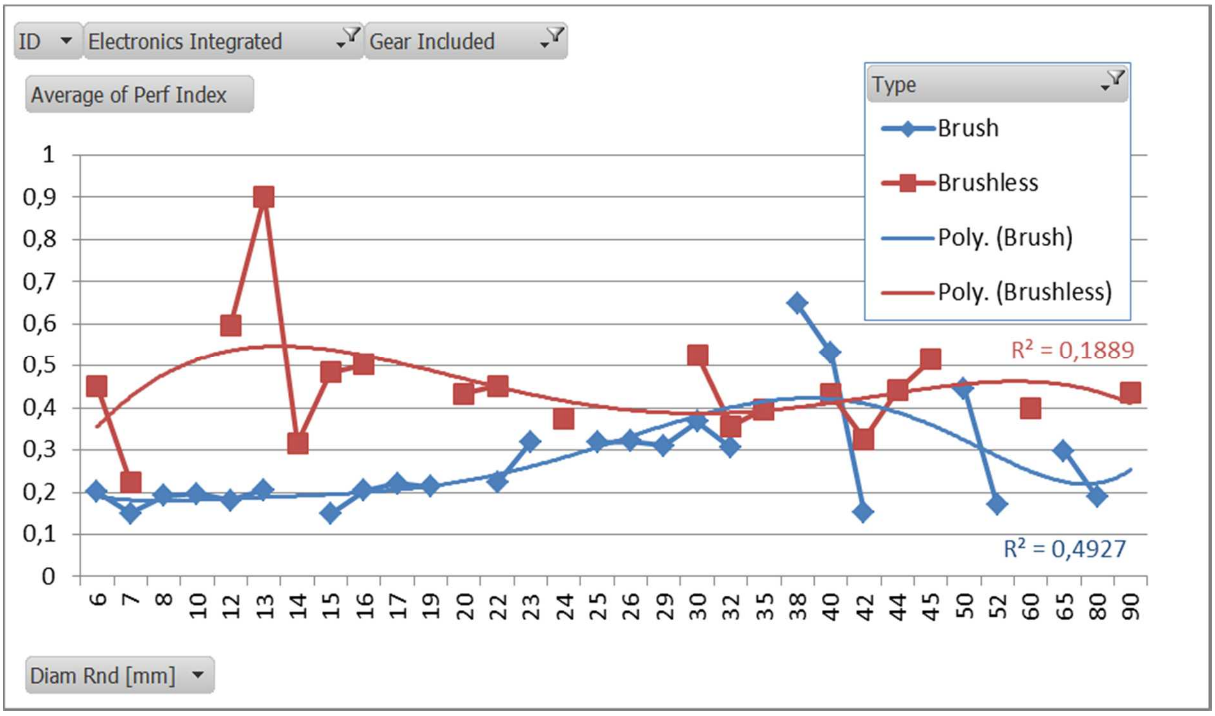

Figure 26. Performance index vs. size. Higher is better.

The performance index in Figure 26 is calculated from torque/volume, power/volume and power/mass, according following procedure and equations:

- Each of the three arguments is firstly normalised by scaling them from 0..1 over all data records.
- Then average of overall arguments is taken for single record.
- Finally value is scaled to 0,1..1. Lower boundary is limited because of €/performance calculation at next graph. This will prevent that index is never zero.

Value 1 for performance index would indicate that the motor is superior over all other compared motors at all measured performance aspects. Value 0,1 means the opposite.

Brushless motors seem to have generally better performance. They seem to have better performance especially at sizes 6..25 mm and 43..90 mm. Brushed motors have optimum at 30..45 mm.

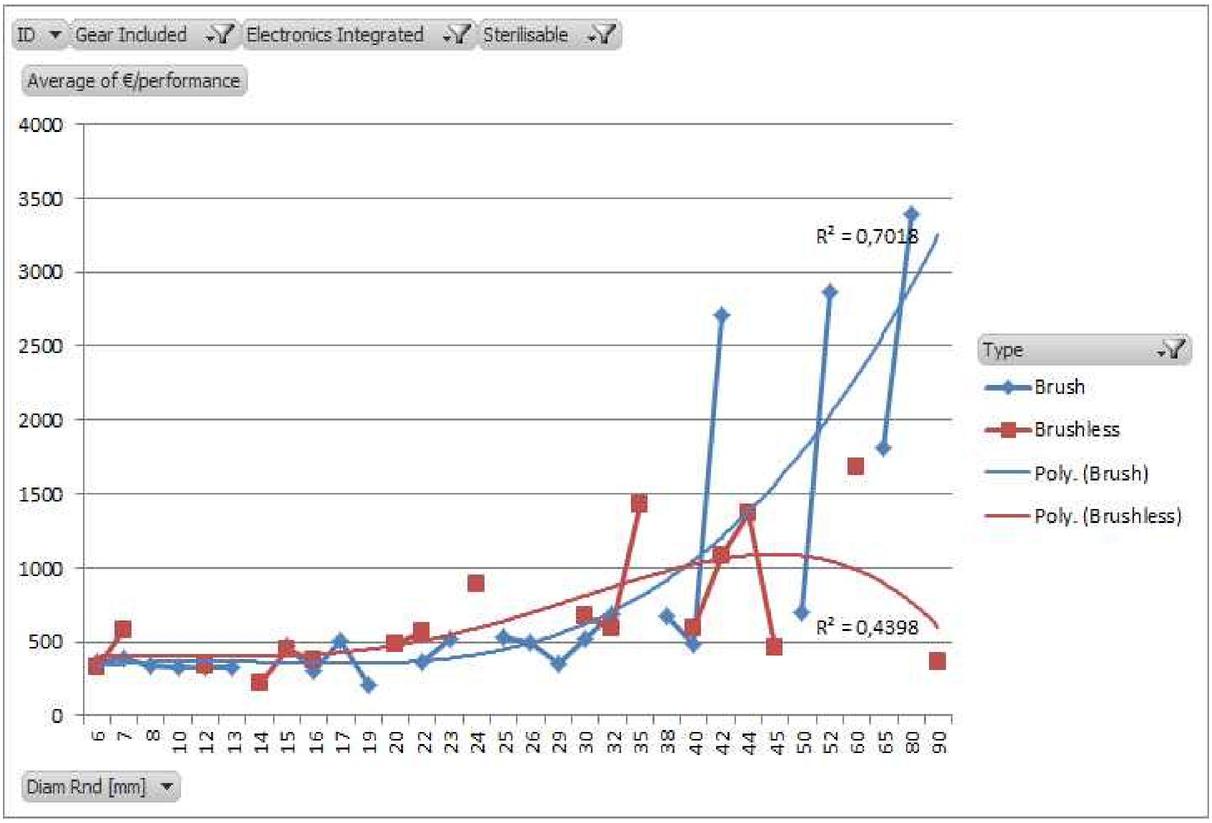

Figure 27. Price (EUR) per Performance index vs. size. Lower is better.

Figure 27 shows the performance penalized price of the different motors.
Equation: Price of motor / performance index
Performance index is limited to be in worst case 10x the price of the motor (Performance value varies between 0,1..1). The best motor from performance point of view will get directly the price of the motor.

From price per performance graph can be noticed that both type of motors are quite in the same at smaller motor sizes. Brushed motors are even a bit better and remain competitive a bit longer as the motor size increases. The brushless motors start to rule when the motor size gets larger than 42 mm. The data used in the analysis does not include enough samples at large motor sizes. Therefore the downwards bending end of brushless motors trend line should be doubted.

5.3.2 Stepper Motors

Analysis of stepper motors includes 23 motors from two suppliers, with motor sizes ranging from 28 to 106 mm.

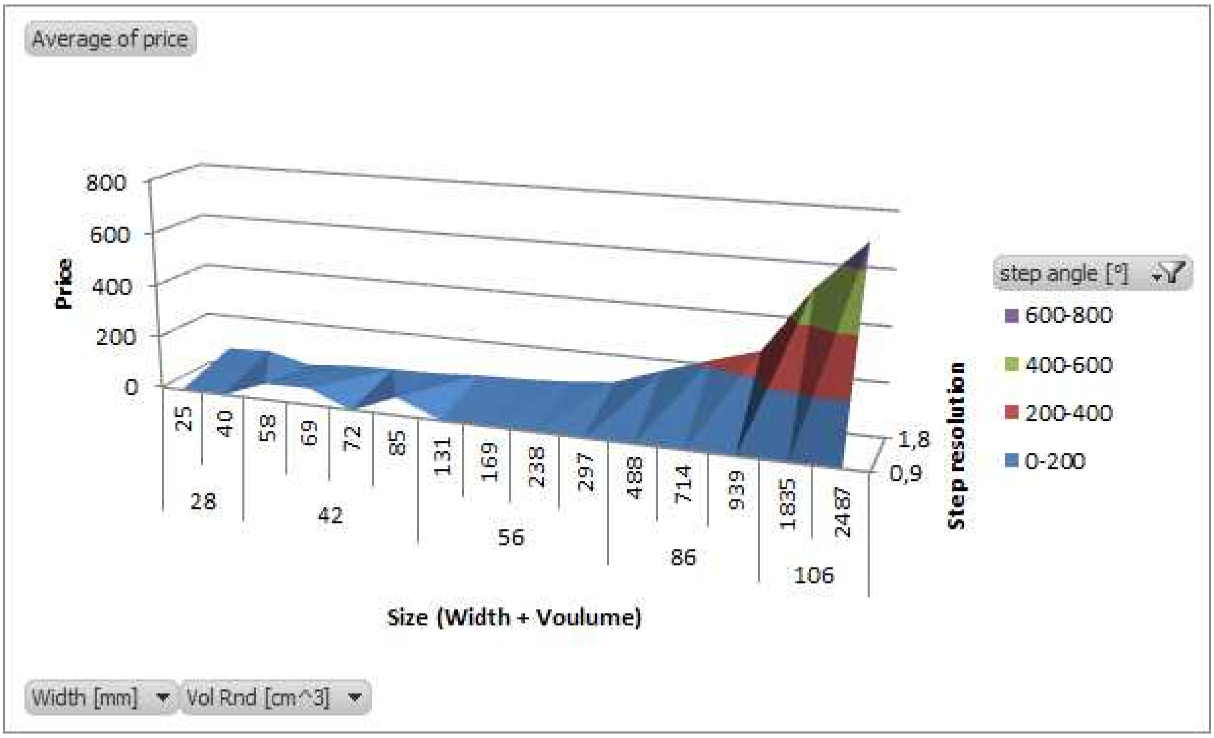

Figure 28. Price (EUR) vs. size (volume) and accuracy. Lower is better. (Notice: No data equals zero. Notice2: higher accuracy motors with small step resolution are at front)

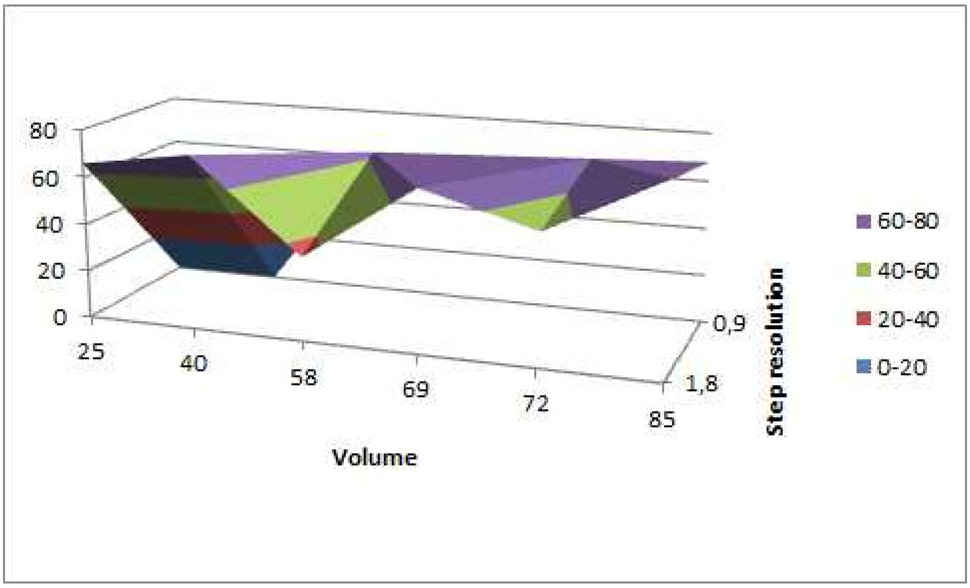

Figure 29. Price (EUR) vs. size (volume) and accuracy. Detailed view of smaller sizes, with some zero values eliminated with interpolated values to have a continuous graph. Lower is better. (Notice: No data equals zero. Notice2: higher accuracy motors with small step resolution are at behind)

Figure 28 and Figure 29 show that both accuracy and the size of motor increase the price. Price optimum seems to lie in size of 42mm width (Volume 58cm^3).

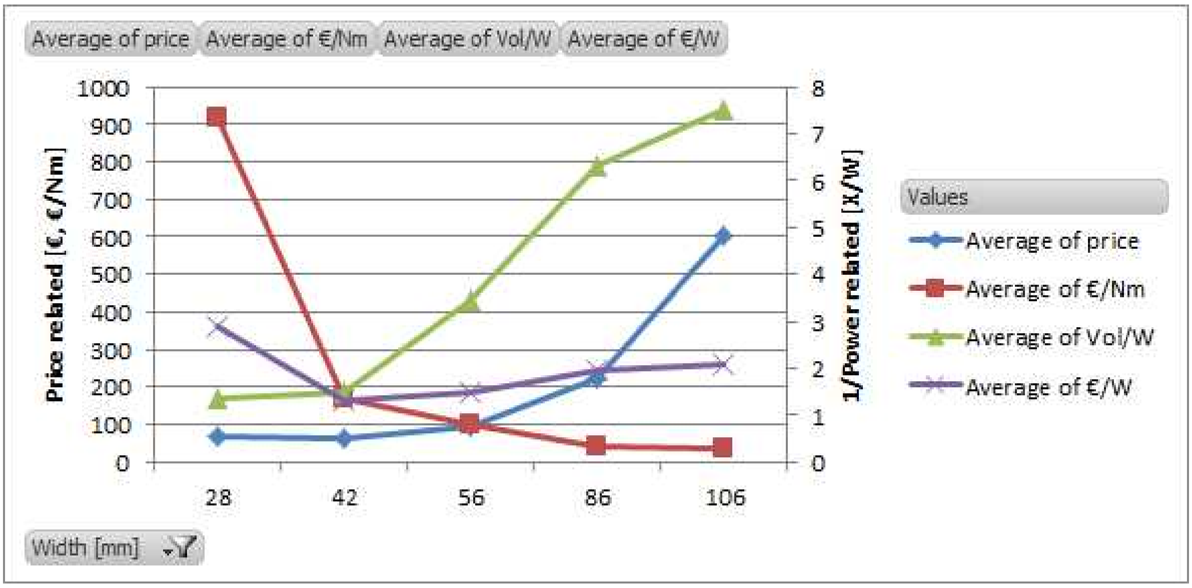

Figure 30. Price (EUR) vs. Size. Lower is better, except Vol/W(green) that is higher better.

From Figure 30 can be concluded that the price optimum is on size of 42mm. Both larger and smaller motors are more expensive. The optimum for price per power is on the same size. Price per torque is still reducing at larger ones, but the largest drop happens before this size. The optimum for volume per power is on larger sizes. Optimum seems to be in the stepper motors width of 42 mm. The reason for this could be on scales of volumes as that size is the most widely used of the industrial stepper motors.

5.3.3 Gears

5.3.3.1 Planetary

Analysis of planetary gears includes 137 gears from three suppliers with size range from 6 to 81 mm.

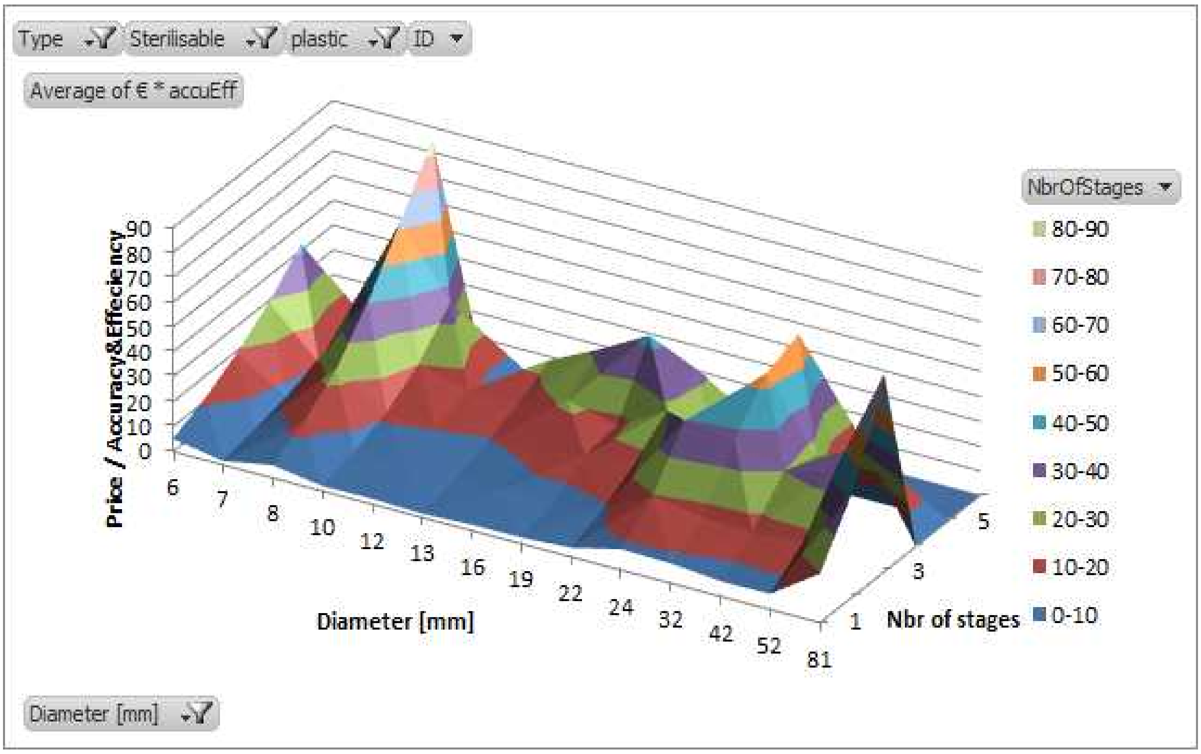

Figure 31. Planetary Gears: Price per (accuracy and efficiency) vs. size vs. number of stages. Lower is better.

Figure 31 above has three axes: The diameter of the gear, number of stages and evaluation value as function of the two previous ones. Evaluation value, i.e. the price per accuracy and efficiency, is created as follows: Accuracy is the backlash of a gear divided by the maximum backlash of all compared gears. This value is on range of 0..1. Efficiency is the efficiency of the gear and, for the calculations, it is inverted so that lower value is better and it is never zero (i.e. efficiency is never 100%).

Eq: $F(x,y) = Price \times \left(\frac{Backlash}{Backlash_{Max}}\right) \times (1 - Efficiency)$

Sterilisable and plastic gears are excluded. A general finding is that, the lower the number of stages, the better the price performance ratio. This is understandable as the price increases according the amount of stages meanwhile the accuracy and efficiency drops when more stages are added into the gear. This can be seen as increase of price performance value as the number of stages is increased. However, the valleys (from front to back) in the graph are the points of interest as they do offer better value and quality for money (see for example sizes of

7, 10..16, 22, 42..52 mm). These valleys could partially originate from higher production and sales volumes.

The three dimensional plot shown in Figure 32 and Figure 33 represents how much torque the gear is able to produce or take compared to its volume (higher values are better). The plot shows that gear sizes 8, 13, 22 and larger than 32 mm are capable of providing relatively large torques per volume. Gears with six, five or four stages are available only in few sizes and therefore the plot has many zero values on the “back side” (high number of stages). In practise, it would be expected that the plot rises higher with higher number of stages.

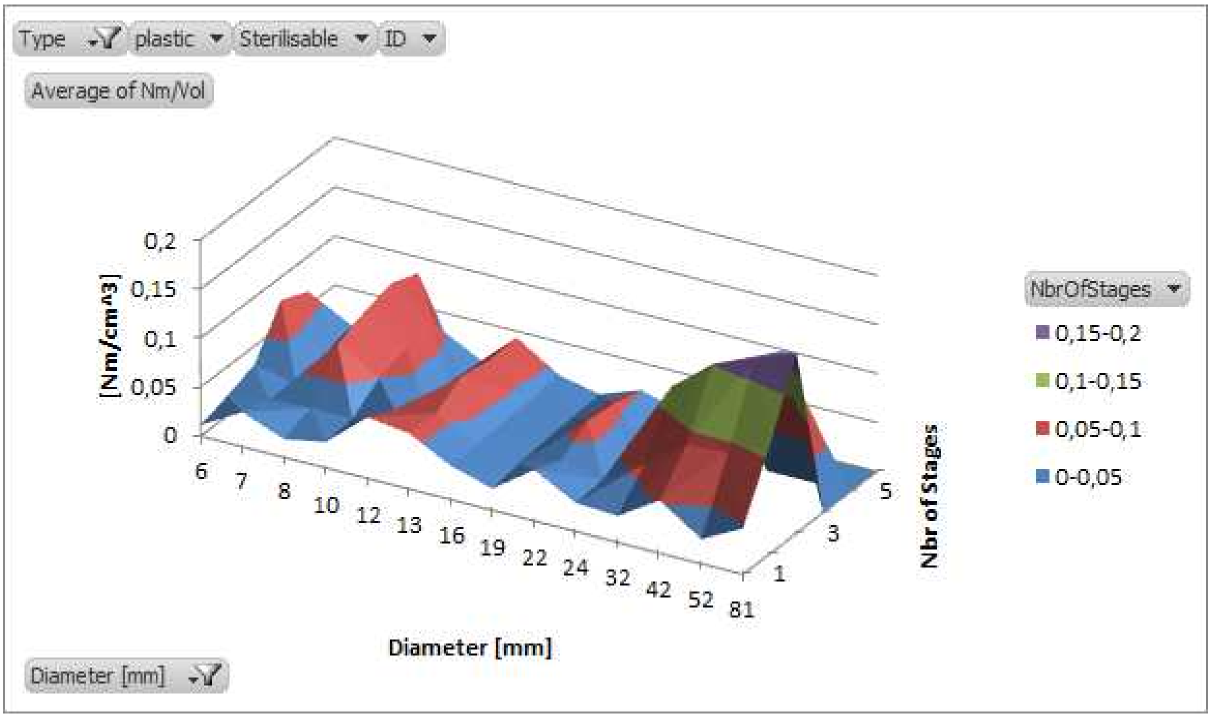

Figure 32. Planetary Gears: Torque per volume vs. size vs. number of stages. Higher is better.

Regarding Figure 32, please note that plastic gears are excluded, but sterilisable are included. Also not all gears have all different stage configurations available. This is especially true in case of six stages, which is only available in size of 8 mm.

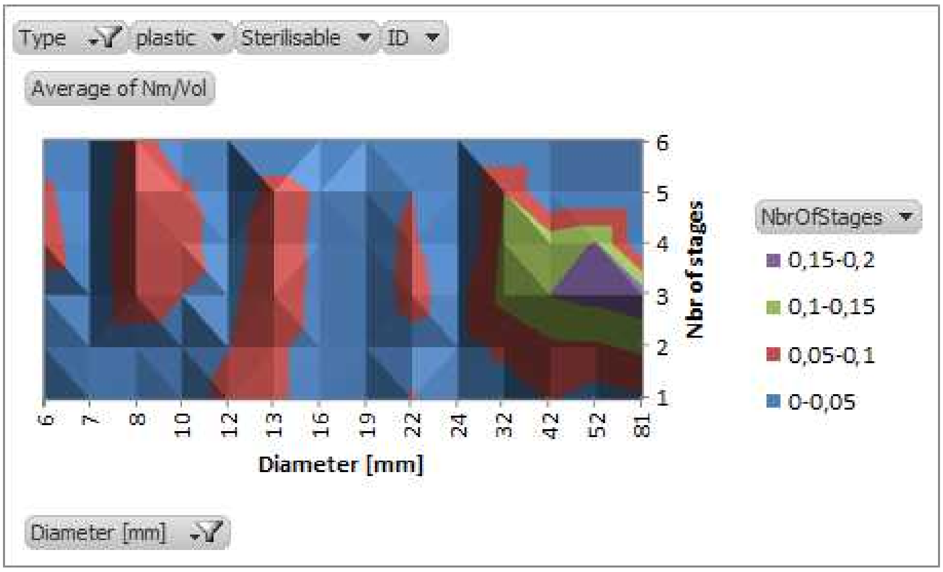

Figure 33. Planetary Gears: Torque per volume vs. size vs. number of stages. This is the same as Figure 32, but from top view. Higher is better.

When summarising previous three figures together, it can be concluded that optimum sizes for planetary gears would be 13, 22, 42 and 52 mm.

5.3.3.2 Spur Gears

Analysis of spur gears includes 56 gears from three suppliers with size range from 10 to 45 mm.

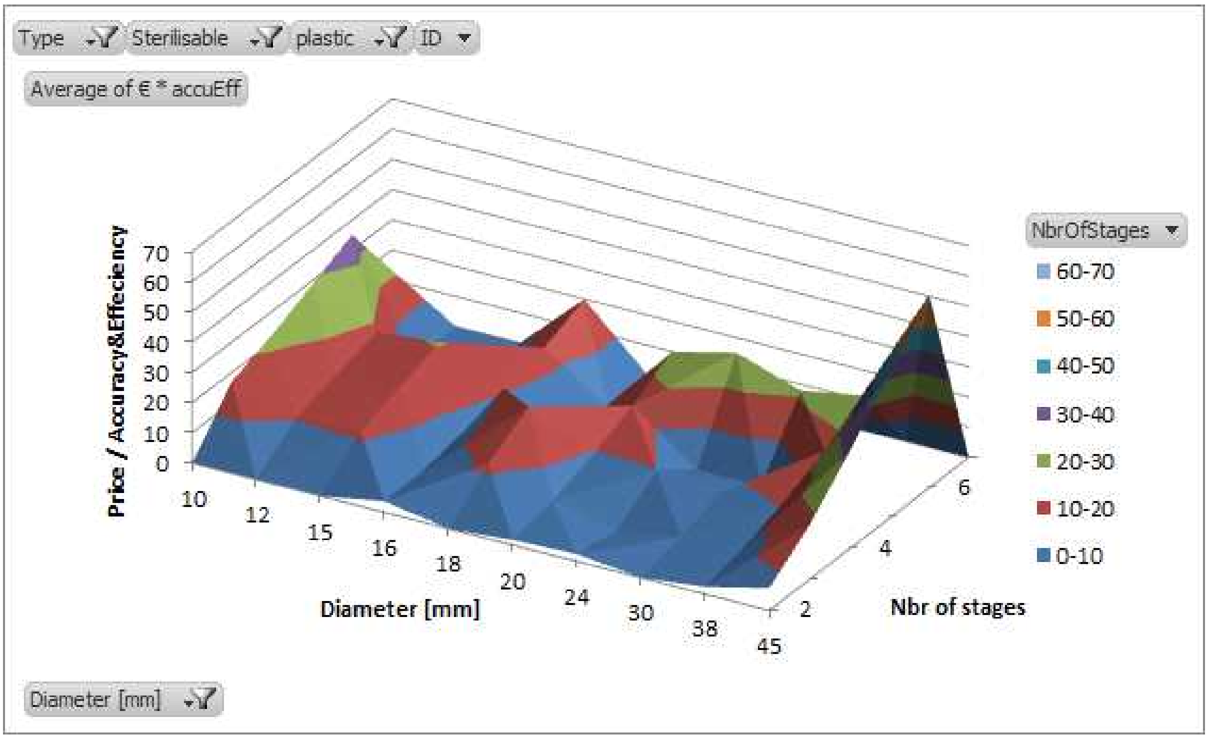

Figure 34. Spur Gears: Price per accuracy and efficiency vs. size vs. number of stages. Lower is better. Notice: No data equals to zero (holes on graph), and not all sizes have 7 stages.

The graph in Figure 34 is quite flat and rough. Therefore absolute optimums are hard to state. Sizes 12, 16, 20 and 30 mm show slightly better values and the smallest and largest sizes are far from optimum.

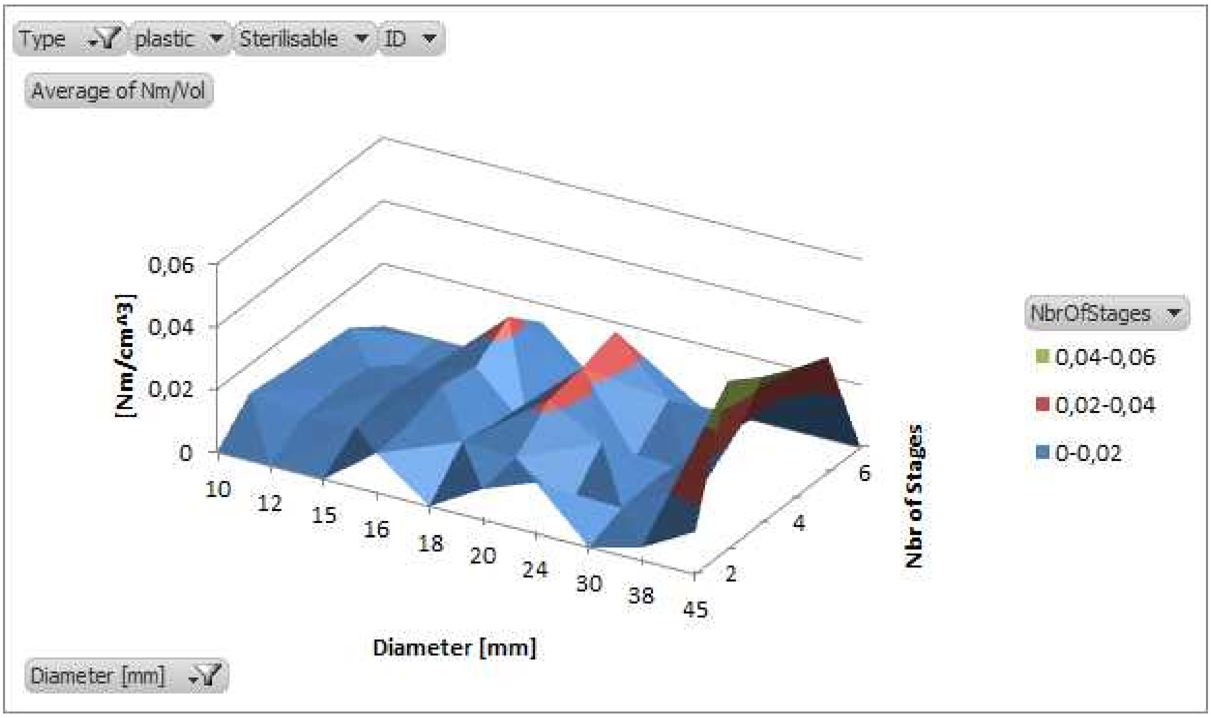

Figure 35. Spur Gears: Torque per volume vs. size vs. number of stages. Higher is better. Notice: Plastic gears are excluded.

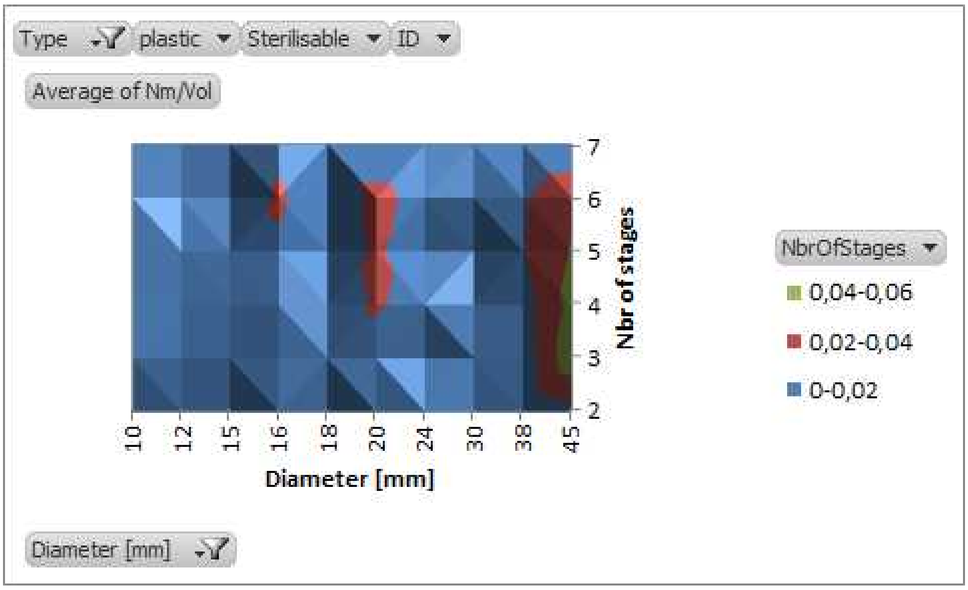

Figure 36. Spur Gears: Torque per volume vs. size vs. number of stages. Same as Figure 35, but from top view. Higher is better.

According to Figure 35 and Figure 36 the optimum sizes, from the torque per volume point of view, would be sizes 16, 20 and 45 mm. When summarising the results from the previous three figures together, it can be concluded that optimum sizes for spur gears according the collected data are 16 and 20 mm.

5.3.4 Linear Guides

No data was received from the requested sales organisations. In some sense this is somehow understandable. When analysing the field the heterogeneity became quickly visible. It was not even easy to define what are the parameters one should compare. For example, the order sheet had several configuration dimensions and some of the parameters were freely definable (e.g. length), leading into infinite number of parameter combinations.

The discussions with salesmen pointed out rough trends. Making a step at next accuracy class will increase prices by 10%.

5.3.5 Ball Screws

Analysis of ball screws includes 19 screws from one supplier with thread size range from 3 to 22 mm.

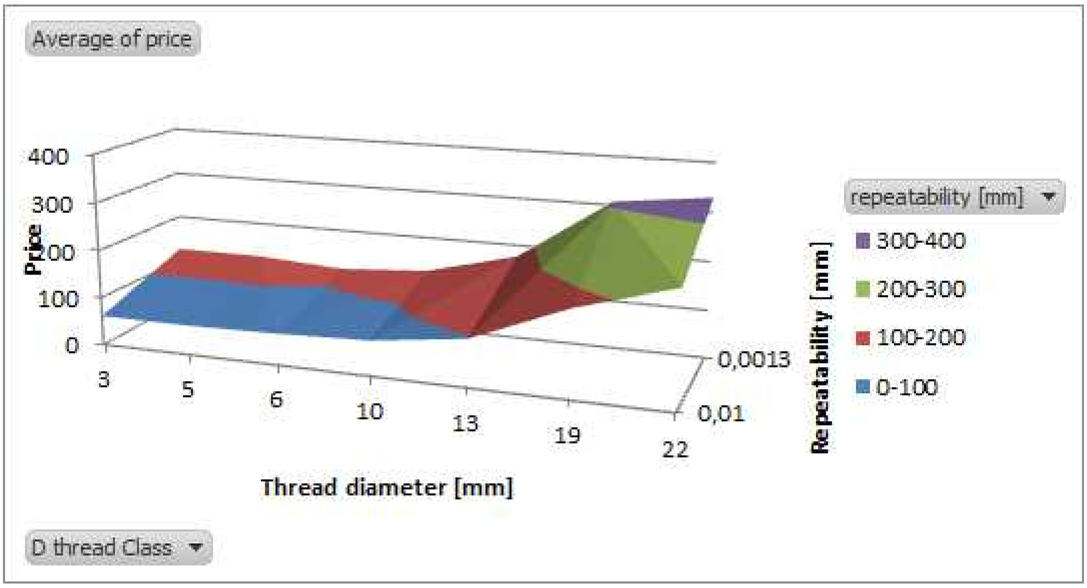

Figure 37. Price vs. screws size vs. repeatability. Lower is better.

From Figure 37 can be noticed that price of screws increase as a function of increasing size and accuracy, which would be a logical assumption. However, the statistical set is too small for making any general statement. Stepping from 0,01 mm repeatability class to 0,0013 mm (i.e. to one decade better accuracy class) the average price increase is 70%.

5.3.6 Encoders

The price of encoders usually does not have size effect. The same sized components or sometimes even the very same components are used for different accuracy classes and resolutions of an encoder. In some cases, just the packaging of the sensor may be slightly different because of mounting configuration or followed interface standard. Instead, the used sensing technology will have a bigger effect to the size of the sensor. For example, optical and magnetic based solutions have differences in size and also in properties such as resolution and accuracy. Same applies to both linear and rotational encoders.

5.3.7 Machine Vision

"Traditional" machine vision components are usually unnecessary large to be easily used in desktop size equipment. Luckily one development trend also in Machine Vision components is miniaturization: more and more (camera) manufacturers are releasing smaller than ever camera systems. Figure 38Figure 39 Figure 40 below show examples of currently commercially available small size camera systems from different manufacturers.

Figure 38. Board level camera (36 x 36 x 20 mm) with S-mount optics connector and enclosed camera (44 x 44 x 25 mm) with normal C/CS-mount for optics. Both have USB 2 interface. (http://www.ids-imaging.com/) On right, "subminiature" camera (size 16x16x13 mm) with M12 lens mount from Ximea (http://www.ximea.com)

Figure 39. Board level camera (32 x 32 x 7 mm) without optics connector and camera system with one or up to four remote camera heads (remote head boards 28 x 19 mm, central unit about 42 x 38 mm). Remote camera heads use user selectable lens mounts. (http://www.vrmagic.com/)

In addition to “plain” cameras, manufacturers are miniaturizing camera systems with additional features integrated to them. Figure 40 shows one of the smallest currently available smart cameras (image and result processing integrated to camera housing) with housing dimension 44 x 44 x 44 mm (excluding C/CS mount optics). Other models have integrated lens and focusing functionality into extremely compact housing of only 23 x 23 x 26 mm.

Figure 40. On left, smart camera from Teledyne Dalsa (http://www.teledynedalsa.com/). On right, miniaturized camera manufactured by IDS Imaging (image from http://www.1stvision.com/cameras/IDS/UI-1008XS-C.html). It seems that IDS has discontinued this camera family.

5.3.8 Controllers

Controller requirements for assembly and manufacturing processes in case of microfactories are defined by the needed basic functionality. In general, motion control and machine vision are needed, sometimes also communication to other applications or devices. As machine vision requires relatively large computing capacity, PC-based control is the easiest selection. Alternative for PC is distributed intelligence, meaning that components with integrated processing (i.e. smart cameras) are used. Compromise is between functionality, integration time and unit price. As modern PC-technology offers huge computation power in a small and price competitive units, it could be seen as primary computation resource. Modern PC-technology offers huge variety of platforms and frameworks. Selection bases on the required interfaces and supported operating system (OS). OS dependency in highly integrated PC-platforms is the most critical factor when the third party software and software libraries are to be used.

Mobile platforms offer huge potential in terms of computing power, size and price. As technologies in such platforms are developed for consumer markets only, the software platform is generally very integrated, limited and closed. Significant amount of development work is needed if such platform is applied in industrial use. Availability of third party software libraries (e.g.. machine vision) is a key factor in selection of highly integrated embedded control system platform.

Motion control tasks are requesting deterministic controls, fast cycle time, and calculation power for meeting the calculus for each control cycle. In case of complicated kinematics with interpolated movements or in cases when the same controller is responsible of controlling several axes simultaneously the requirement for motion control increases. Solutions are manifold: central controller with high calculation power and fast communication channels; distributed local controllers taking care of only a few axes; use of dedicated and specialised motion controllers; distributed motion controls at drives or amplifiers; etc. Different solutions need to be evaluated for application requirements and selecting the best for each case.

If machine vision or other computation power intense technologies or external library dependencies are not needed, development of custom controller is significantly easier and cheaper. Operation system requirement usually becomes necessary if specific communication interface like Ethernet, EtherCAT / ProfiNet / Ethernet / IP, CAN / CAN-Open or other higher level communication interfaces are to be used. Development of custom processing board with operating system support is expensive process, and special hardware (HW) and software (SW) knowledge of embedded devices is needed. Processor selection bases on the OS support. Special embedded operation systems such as linux, QNX, rtems etc. usually offer real time capability or real time versions, but commercial libraries for machine vision, communication protocols, etc. have variable support. End user support for such subsystems usually limits on MS Windows based applications alone.

The selection of the control architecture and controller is one of the major decisions. One of the first decisions is the selection between standard off-the-shelf solutions versus embedded custom development. The former has usually the advantage of well proven platform with tested software tools. Industry is familiar with these devices and tools used. Programming is made at higher level and usually numbers of (standard) hardware and communication interfaces are supported. The development of the application can be made much faster from control side and there is fair possibility that the parts of the code or libraries can be used across different products or projects. The drawbacks are form and size (occupied volume, shape, orientation of interfaces, used connectors, etc.); device and tools might have plenty of unnecessary functions, leading to high cost and complicated use and configuration; tight dependency of decisions of external player (availability of components both at short term i.e. capability to fulfil orders and in long term i.e. spare parts).

The latter offers tiny embedded controllers which are characteristic by: space fitting form and shape so that the hardware fits perfectly to the given space which is often very limited and odd shape at microfactory applications. Connectors are selected for application needs and they are located at optimal places; optimised functionality. The controller meets exactly the given requirements; company can protect better their intellectual property as it is taken down to the hardware level. The drawback of this approach is the high cost and longer development cycle of controller HW and SW. The same affects also negatively to the response to changes in the requirements. E.g. if later appears a requirement of additional port, it might require major redesign starting from the HW level; the quality of the HW and SW is sometimes questionable as solutions are not as mature as the ones with standard, industrial and better tested solutions; uncertainty of the payback if volumes are not increased as planned.

The second decisions made with control solution relates to modularity and granularity, which are important aspects especially in case of the off-the-shelf controller components. The controller CPU and the IO are usually constructed in modular fashion. We have found some IO modularity concepts better fitting to microfactory sized environment like the ones provided by Beckhoff, Wago or Crevis FnIO. In these there is no backplane frame reserving a fixed space, but each module adds only smaller slice to the whole. Even more important factor is the ratio of HW volume per IO connection point. This ratio should be as small as possible. These are the factors which determine does the device fit into the available space.

The developments made at drives and amplifier side are also welcome from microfactory development point of view. Some vendors have been able to compress the size of devices to really small (like Maxon, Faulhaber, Elmo, to name some) and still increase the power that can be connected through the device. In some cases also the integration and intelligence level of drives has been increased by adding communication capabilities and (several) feedback interfaces into the same package.

The main questions in case of controls for microfactories are the selection of control approach (standard versus custom development), control architecture, modularity, shape and size of devices, minimising the volume per IO point, available processing power and maximising the needed functions per available functions.

5.3.9 Conclusions of Components

According the information collected mainly from motors and gears, the hypothesis stated at the beginning of chapter 5.3 and in Figure 20 (there is a price optimum in component size and that optimum lies in the desktop size range) seems to be only partially true or at least not fully proven. Studying only the component prices does not reveal the inevitable increase of prices when the component size is getting really small, at least not in the product range used for this study. The price of small components (e.g. a motor) starts rising when the component size is getting extremely tiny like diameter around few millimetres or less. However, it can be questioned if such motors are applicable at all, and at least they are not commercially available in large scales.

Two certain costs, which will rise in case of tiny components, are the handling and assembly costs, which were not studied here. To integrate a small motor to a machine, the assembler needs to deal with tiny wires, connectors, screws and other components. This all requires much more concentration, dexterity and accuracy that all sums up to that more time and costs are used for assembling the machine. Similar aspects start to arise at the other end, when component sizes are getting too large to be handled by human and e.g. if different kinds of lifting aids are needed. This way the overall costs will be increased in case of small components as hypothesis expects, but this was not visible in the component price versus size study made here.

A general conclusion can be made that accuracy (visible from threads and guides or stepper motors) and amount of parts in a component (visible from gears) increase component prices. Therefore, as general guideline, one should select the accuracy and performance level that is just enough for the application. For a specific type of component, there often exist various points of optimum. This is clearly visible from gears (e.g. Figure 31) and partially from the motors. This depends on the component supplier pricing policy, supplier itself, and also one’s own optimisation aim (see motors analysis as an example). Therefore company buying components for their own products should make carefully their own analysis.

6 Vision of Future Micro- and Desktop Manufacturing

In general there are two envisioned main development directions for the micro and desktop factory solutions:

1) Small size stand-alone equipment assisting human operators on the desktop
2) Small size equipment forming fully automatic production lines (including line components, modules, and cells)

In both development directions the main development driver is pursue for lean and agile production. Through these, the manufacturing companies try to improve product properties (quality, customization level, etc.) and/or increase efficiency and profitability for example by decreasing the costs per sold product. In addition to hard economic objectives, also “softer” drivers for new manufacturing technology are emerging. For example, one rising trend in the industrial world has been sustainable manufacturing and different “green” initiatives. These “lean, green and agile” are the root objectives that can be used as arguments for all other secondary objectives such as “small production facilities for small products”.

This section will first discuss Competitive Sustainable Manufacturing (CSM) and Lean manufacturing and their relationship to micro and desktop manufacturing. After those, vision about the characteristics of future desktop manufacturing systems will be drawn, followed by the challenges and limitations relating to micro and desktop manufacturing. Next, the vision of the potential application areas and production types will be discussed. Finally the visions from different actors, namely end user, equipment provider and system integrator, point of view will be drawn followed by business models for system integrators and equipment providers.

6.1 Competitive Sustainable Manufacturing (CSM) and Desktop Manufacturing

The European level strategic goal towards Competitive Sustainable Manufacturing (CSM) calls for the Sustainable development consisting of three structural pillars namely society, environment, and economy. According to Jovane et al. (2009), sustainable manufacturing must respond to: 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; Environmental challenges, by promoting minimal use of natural resources and managing them at the best while reducing environmental impact.

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. One important social aspect is to ensure the economic well-being of people by maintaining and improving their jobs. Micro and desktop factories offer great potential for improving the social aspects. First of all, they can be used to help human with boring and repetitive tasks letting the human worker to concentrate on more interesting activities requiring special skills, or to eliminate ergonomically difficult tasks. Compared with big production equipment, e.g. industrial robots, micro and desktop factory solutions do not expose the human workers to danger. Due to small forces, for example the collisions are not fatal.

The economy pillar of the CSM calls for economic growth, global competitiveness and capital efficiency. From economic point of view micro and desktop factories are also promising, because of smaller investment and running costs compared with the traditional size production systems. The cost-effectiveness offers one good weapon against the production shift from Europe towards low labour cost countries. This relates also to the social aspect of trying to maintain the jobs in Europe or even bringing them back.

The environmental changes, such as global warming, have forced the manufacturers to think not only economical, but also environmental aspects, e.g. in terms of consumption of resources (energy and material), emissions, waste and so on. Two very concrete requirements for the production systems are reduced energy consumption and reduced space. While currently small products are still produced with large, space consuming, machines, it is seen that reducing the size of the production equipment closer to the size of the produced product could simultaneously not only reduce the space requirements and energy consumption, but also produce less waste in terms of raw material, heating, cooling, etc.

6.2 LEAN and Desktop Manufacturing

Lean is a production practice, pioneered by Toyota, that considers the expenditure of resources for any goal other than the creation of value for the customer to be wasteful, and thus as a target for elimination. The customer can be either external or internal customer (i.e. next phase in the process). Lean can be defined as a five-step process: defining customer value, defining the value stream, making it “flow”, “pulling” from the customer back and striving for excellence. To be lean the manufacturer requires a way of thinking that focuses on making the product flow through value-adding process without interruption (one-piece flow), a “pull” system that cascades back from customer demand by replenishing only what the next operation takes away at short intervals, and a culture in which everyone is striving continuously to improve. (Liker, 2004.)

The Toyota’s principles of eliminating waste differ greatly from the traditional mass production principles. In Toyota Production System (TPS) non-value-added waste does not have much to do with running the labour and machines as hard as possible, but everything to do with the manner in which raw material is transformed effectively into a finished product.

The point is to eliminate the activities, which do not add value to the raw material. What adds value in any type of process is the physical or information transformation of the product, service or activity into something the customer wants and is willing to pay for. The main thing to do when eliminating waste from the processes is to recognize the activities that add value to the product and get rid of others. All the non-value added processes cannot be eliminated. For example operator has to reach for tools and get new material. The point in eliminating waste is to minimize the time that is used for this kind of operations. (Liker, 2004)

Lean defines seven major types of non-value adding waste in business or manufacturing processes. Shortly put, these are: overproduction, waiting, unnecessary transport or conveyance, over processing or incorrect processing, excess inventory, unnecessary movement and defects. The eighth is unused employee creativity. Overproduction is seen as the biggest waste, because it causes most of the other wastes, like huge buffers between the processes. The buffers in turn hide some problems, like quality defects on the line, and decrease the motivation for continuous improvement and e.g. preventive maintenance. One-piece-flow, the ultimate goal of lean production, passes one work piece (or very small batch) from one operation to the next in a flow and results in gains of productivity and quality and big reductions in inventory, space and lead time. The goal is not, however, to blindly apply it everywhere without taking into consideration the specific characteristics of each operation and individual situation. (Liker, 2004)

The following shortly discusses how micro and desktop factories contribute to minimizing the seven wastes identified in Lean:

Overproduction

- Overproduction can be minimized, because microfactories allow small batch sizes. Due to the cheaper equipment, it is more profitable to produce in small batches, compared with traditional size equipment.

Over processing

- Over processing, in some sense, can be reduced by using smaller billets. This also reduces the raw material consumption.
- Over processing can also be related to the unused functions in the production equipment. Modular microfactories enable customized flexibility, which means that the production system can be built to the exact need eliminating the unused functions, which cost money or space and do not bring value to the production. However, modularity of the system components requires definition of interfaces, which may not be used, but which cause extra costs.

Waiting

- Since the transfer distances between production stations are short, the waiting times between the stations can be minimized. For example, a human operator can move products directly from one microfactory module to another while sitting behind his/her desk.
- Small batch sizes minimize the amount of unfinished products and, therefore, the time that the products need to wait before going to the next process step.

- Waiting can also be reduced by distributing the production capacity, for example there can be two different microfactory lines producing two different products. Instead of expensive monolithic system which is used to produce different (and larger) batches in sequence.

Transportation

- Desktop factories enable moving the production to the most convenient locations, for example the manufacturing on the spot, i.e. close to the place where the product will be actually used. Therefore the transportation of the finished products can be minimized.
- On the other hand, micro and desktop factories allow the production in small spaces, which should also reduce the distances between the production stations and storages, i.e. bring the raw material and parts closer to the production unit, and therefore reduce the time used for transportation.
- Smaller production devices make it possible to bring machines close to the operator and thus minimize non-beneficial buffers, internal material logistics and waste related to material transportation.

Excess inventory

- Excess inventory is reduced by manufacturing small batch sizes.

Unnecessary movement

- Microfactory can be lifted on the manual worker's desktop. This means that the parts and products are close to the worker eliminating the need of the human to move around to the get the parts and products.

Defects

- Processes performed with automated microfactory units require sensoring. These same sensors can also be used for continuous quality control. This way the defects can be identified in each station and the faulty products can be removed from the line before letting them proceed to the next station (or they can be neglected in latter processing steps).
- When machine is working with close interaction with the operator, visual inspection and quality control can be easily done without buffering products. Possible faults will be noticed in early phase, and feedback loop to production remains short.

6.3 Characteristics of Future Micro And Desktop Manufacturing Systems

Westkämper introduced the roadmap towards adaptive manufacturing in 2006 (Figure 41). Most of the ideas and key topics presented in Westkämper's Manufuture Roadmap apply also to the future micro and desktop factories. However, due to Manufuture Roadmap's generality lots of ideas and key topics related to future micro and desktop factories are missing. In this chapter, we introduce our vision of future micro and desktop factory technologies and systems and discuss in detail the most important characteristics from the micro and desktop factory point of view.

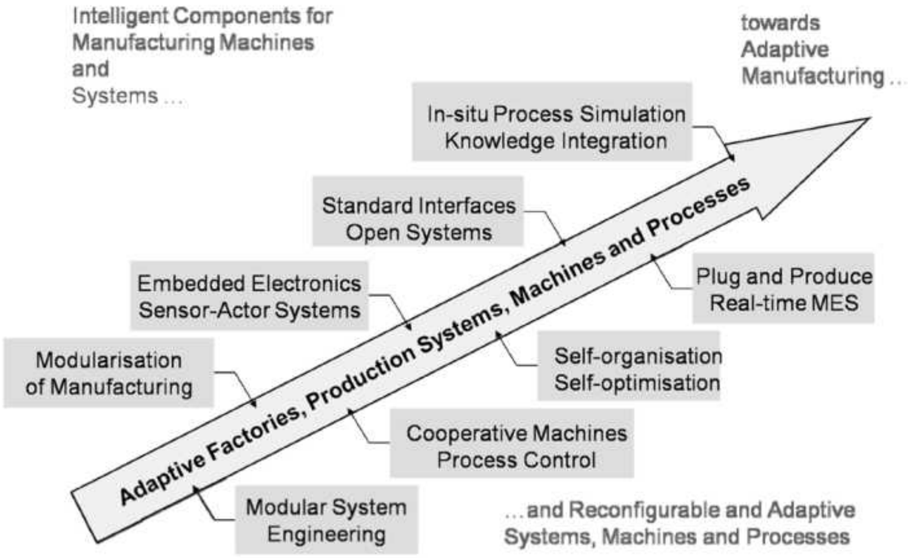

Figure 41. Manufuture roadmap (Jovane, 2009)

Our vision of future micro and desktop factory technologies and systems is presented in Figure 42. It takes into account the characteristics of manufacturing systems, but also processes and products that are manufactured using micro and desktop technologies. Additionally, relations and influences between manufacturing systems, products and processes are presented.

Future manufacturing and production systems are often described with adjectives such as reconfigurable, evolvable and holonic. These can be applied also to micro and desktop factories. Progress towards that kind of systems requires the development of interfaces, modularity, usability and self-diagnostic. Additionally, improved performance of micro and desktop systems enables new more challenging manufacturing processes.

One of the most important milestones during the progress towards future micro and desktop systems is standardization of interfaces and architectures. It is a prerequisite for the development of true reconfigurable, evolvable and holonic manufacturing systems.

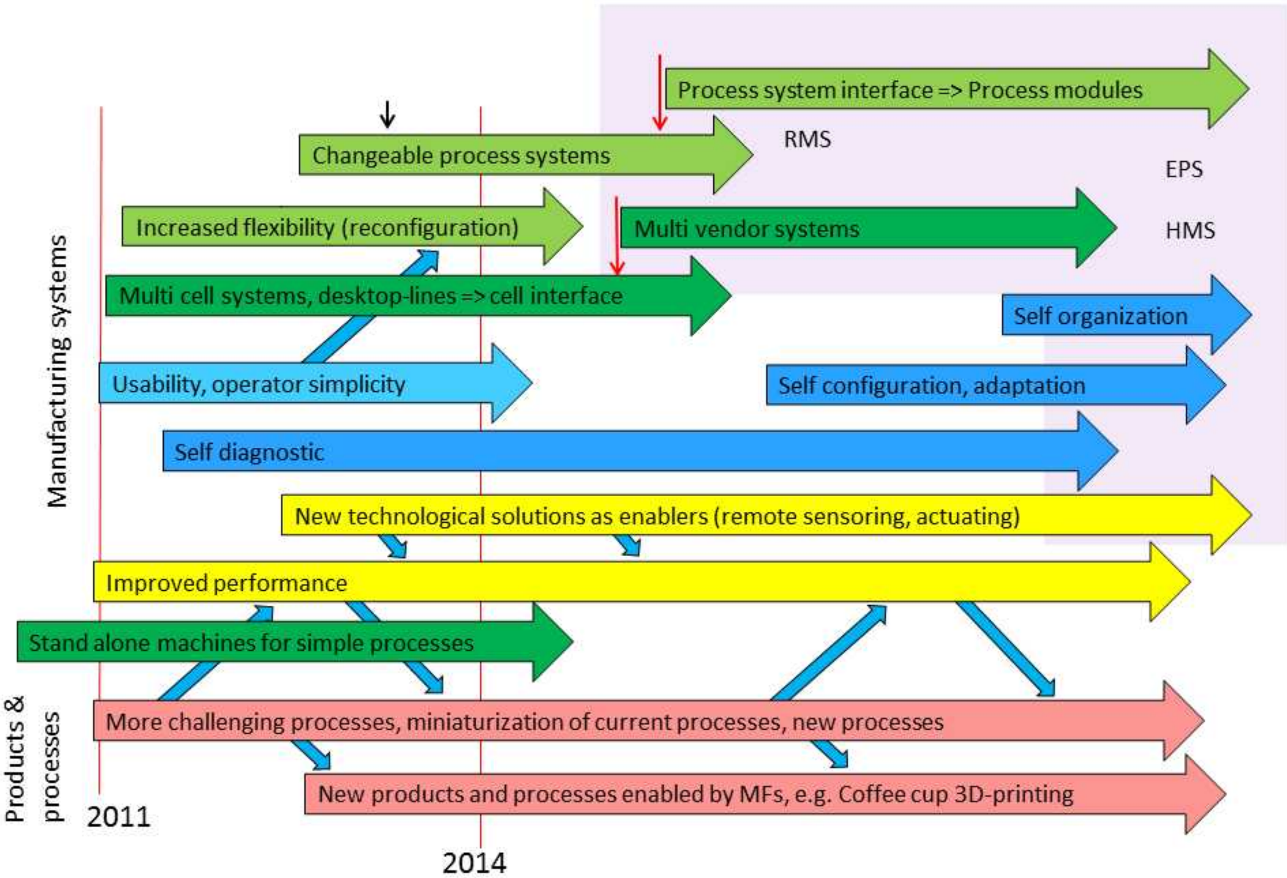

Figure 42. Micro and desktop factory technology roadmap

The following shortly lists and describes the characteristics of future desktop manufacturing systems (and many of these apply also to larger equipment):

Small and challenging processes

Components and parts are getting smaller, but still processes need to be performed to products. Often the processing tools and devices are relatively large, but they still need to be brought closely to the point of process. This means that, even more often, the operator access to directly see or interact with the product and process is blocked. Therefore system design and organisation of processes need to focus on providing the best possible access for the operator to see and feel the process. There are some aids such as machine vision or haptic devices to help out.

Appearance of New Products and Processes

Microfactories can provide some new technologies or new processes, which on their behalf will enable completely new products to appear to markets. Sometimes just the microfactory, as small sized platform for manufacturing, may be the launcher for economically feasible production. Microfactories could enable completely new business models (see 6.8 Business Models for System Integrators and Equipment Providers).

Highly integrated modules, no separate control cabinets

In future systems, the modules as well as components are highly integrated. Modules are self-contained and all control HW is integrated inside or together with the module meaning that large auxiliary power sources or control cabinets, sometimes several times the size of the module itself, are to be avoided. This means also that the integration level of components will be increased especially if this leads to better performance, smaller volume, ease of use and, and most of all, reduced overall price. Good example of such could be axes and drives. Gear, sensors, position feedback, drive and communication interface are integrated to a motor or axis. Wiring is reduced to power and communication.

Easy mobility (desktop definition)

The devices and components are easily movable by a human without any lifting aids. Easy mobility also enables, at least in theory, easy geographical relocation of production capacity according to changing demands (naturally external logistics might limit this).

Architectures and interfaces

Open, commonly agreed and supported architectures and interfaces are needed. They are the pre-requirement for establishing true multi-vendor systems. In addition, agreed process definitions are needed as enablers for the exchangeable processes modules. These three aspects – architectures, interfaces and process definitions – are needed in order to implement the following four points.

Scalability and integrability

The future production systems are easily scalable. The old manual processes can be automatized one phase at the time, i.e. the automation level of the system can be gradually increased. This requires that the new automated systems are easily integrated to the overall system in a plug-and-play manner, which means that the new production cells need to be compatible with the old systems and the interfaces between the manual and automated operations are efficient.

Modular, plug-and-produce

The previous characteristics, scalability and integrability, require that the system components are modular with standard interfaces enabling plug-and-produce integration and building of new configurations. The requirement for modularity and standard interfaces applies to cell to cell, process equipment and control interfaces, both hardware and software. Standardization of interfaces will allow building microfactory systems from components coming from multiple vendors.

Fast and inexpensive design and building of the systems

The previous characteristics minimize case/project specific design and engineering work thus enabling better profitably and also faster delivery and production ramp up times which lead to better reactivity to rapidly changing needs. The system engineering tools need to support this work and be capable to deal with modular systems.

Reconfigurable and adaptable

Today's manufacturing industry has to cope with volatile production environment characterized by frequently changing customer requirements, increasing number of product variants, small batch sizes, short lifecycle times of products and fast emergence of new technical solutions. These constantly changing requirements call for adaptive and rapidly responding production systems that can adjust to the required changes both in production capacity and process capability. Reconfigurable systems have been designed to offer rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change in its structure as well as in hardware and software components (Koren et al. 1999; Mehrabi et al. 2000). The components can be, for example, machines and conveyors in whole systems, mechanisms in individual machines, new sensors, or new controller algorithm software. New circumstances requiring the changes may be changing product demands, producing a new product on an existing system or integrating new process technology into existing manufacturing systems. (ElMaraghy 2006.) Easy and automatic reconfiguration of production devices has been a major research trend over the last decade. Despite of wide academic research, reconfiguration of commercial manufacturing devices is still lacking behind.

Usability, including Human-Machine Interfaces

Basic use of desktop manufacturing systems has to be very simple and intuitive. This includes everything from setting up the equipment for basic applications, to operating the system and to performing basic service operations. This leads to the question of how desktop equipment should or could be operated? One answer is to make all feasible operations as automatic as possible. For example for basic pick-and-place operations, the work cycle could be only configured (just showing the picking and placing point(s)) instead of actually programming the manipulator. Similarly, advanced sensors such as machine vision equipment should be very easy, or even automatic, to configure.

Because of their small size, desktop equipment might be difficult to access. Therefore visualising the process that happens inside the machine might be beneficial for the operator. Since the equipment and processed components are often fragile, it might be beneficial if the operator could easily and fast simulate the consequences of the next operation. If the system consists of several cells or modules, accessing and controlling all of them from one device would be beneficial.

Ecological
The future production systems need to be ecological in order to minimize the environmental loads the system causes during its lifetime. This sets requirements to e.g. energy use, resource consumption, reusability and disposal of the system and its components.

Energy efficiency
Energy efficiency is both ecological and economic benefit. The direct savings from reduced energy consumption of small size machines might be quite small; however, the bigger benefits originate from reduced waste heat which needs to be cooled down. Other potential benefit is securing energy procurement since, in some situations especially in developing countries, large amounts of (electrical) power is simply not available.

Economical
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 Asian countries. From the micro and desktop factory perspective, these solutions need to offer a competitive alternative to the traditional and existing production solutions. Also all aspects offering improved performance naturally create economic advantage.

Self-diagnosis
Self-diagnostics is needed to improve the reliability of the equipment and the quality of the products. Important sensor technologies include, for example, machine vision not only in traditional visible spectrum but also in non-visible wavelengths and in 3D. In addition to sensing and measuring, useful self-diagnostic systems need to be able to use the measurement data to decide when something has to be corrected (quality is not what it should be), what is the problem, how it should be corrected and finally adjust the process parameters. These tasks will utilize techniques such as machine learning and artificial intelligence.

Control architectures and platforms
Control issues are not specialised and characterised as much by the micro- and desktop domain than the other matters like mechanical design and physical size. Only the size of the controller HW and its modularity and communication capabilities are playing some role. The methods and techniques used as well as interests and trends present at macro world are directly applicable and interest of controls at micro and desktop domain.

The control area is more characterised by the needs originated from scalability and integration, modularity, plug and produce, reconfiguration and adaption, usability and Human Machine Interface (HMI), fast and inexpensive design and building of the systems, discussed above. In order to succeed on these requirements adaptive and agile control system is needed.

These requirements also point towards to at least some level of distribution in control systems.

Integration and interfaces plays central role and therefore widely accepted and adapted control architectures and platforms ease the system development and deployment. The design and implementation of production modules is getting slightly easier when the backbone for connecting the modules together is fixed.

The control and system design may have different objectives. Generally, the dedicated systems are thought to be efficient, but inflexible. Flexible Manufacturing Systems (FMS) bring the flexibility, but the modules are intended to be too generic and they may contain quite some overhead costs of non-utilised features. Reconfigurable Manufacturing System(RMS) / Evolvable Production System (EPS) is targeting to modular and reconfigurable system that is built from re-usable modules which are just meeting the set requirements and nothing more. Amount of different modules is increased in this case, but they should be simpler and they shall fit better to the purpose. This way the module overhead costs and load from unused features are minimised.

Control architectures and visions related to this field are discussed later on System Integrators Vision (See chapter 6.7.2).

Distributed control

Distributed control is interesting for the micro and desktop field. The concepts and methods applicable at macro manufacturing domain are directly applicable here. We need distribution at controls, because the system is intended to be modular by itself. It does not matter whether distributed control is presented at concept or technology level or whether it is called agents, holons, service oriented architecture (SOA), web services, or something else. Instead, the main aspect is that there exists commonly and widely accepted technology or technologies that support modularity at system level and that enables easy reconfiguration of the components to an operational system that plays easily and well together (one could call this orchestration). This objective sets the requirements for the control system architecture and its agility. This links directly to previous paragraphs discussing of needs for scalability and integration, modularity, plug and produce, reconfiguration and adaption, usability and HMIs, fast and inexpensive design and building of the systems. Distributed and modular control system is a must as it builds the basis for these other requirements.

Self-configuration and organization

In agent-based and holonic manufacturing systems, the system consists of autonomous entities (agents or holons), which are able to negotiate with other entities through well-defined interfaces. The entities are self-aware and able to make autonomous decisions based on their goals. Therefore they are capable for self-configuration and organization. Implementation of agent and holon technologies to micro and desktop factories, as discussed previously, will contribute towards self-adaptive microfactory systems.

6.4 Challenges and Limitations Relating to Micro and Desktop Manufacturing

Desktop size equipment has some challenges that are mainly related to the small size and light weights of desktop equipment. The challenges include high accuracy demands, high movement speeds, vibration, and temperature changes. In large scale equipment, these types of challenges are usually resolved using heavy frames. This is not possible in desktop scale. Instead, alternative solutions have to be used. For example, accuracy can be increased by using active closed loop control and vibration can be reduced by using new stiff, but lightweight materials and structures, such as composites. Also optimising movement control can reduce vibration. Since equipment is small, the effect of thermal expansion is not as big as in large equipment and also here new materials can help the situation. Similarly, due to the small size, the transfer distances are relatively short and therefore the maximum movement speed is not as important as in large scale equipment.

In addition to the mechanical design related challenges, the small size of desktop equipment creates challenges such as weak accessibility or visibility of the work space to the operator and difficulties in service operations. Operator needs to be aware of what is happening inside the equipment and, when direct visibility is limited, other methods and techniques for visualising the work space are needed. Often this requires advanced sensors and measurement methods. Service operations can be made easier with modular structure so that, for example, a broken piece of equipment can be removed and serviced off-line.

One more challenge resulting from the small size of equipment is feeding components. As discussed earlier in this document (see subchapter 'Feeding methods' in chapter 5.2.1 Research Results and On-going Research), some companies prefer tray feeding. Large component trays and small equipment are difficult to match, and therefore additional equipment for unloading components from trays or alternative feeding methods is needed.

Limitations relating to micro and desktop manufacturing mostly relate to the size of the equipment: large components or products cannot be handled in small machines. Technical challenges such as those mentioned above might create limitations in some cases and applications. Currently micro and desktop manufacturing is still new and at least partially unproven technology and therefore some prejudices against it probably exist. Also the availability of small size equipment and components is currently limited and therefore small size equipment might not be a practical or economically feasible solution.

6.5 Vision of the Potential Application Areas

This section will draw a vision about the possible application areas where the microfactories could be used in the future. Both the microfactories' role in different supply chains and the potential industries and applications will be covered.

The use of microfactories is categorized into three principal scenarios: I) miniaturization of production equipment in a traditional production and supply chain, II) relocating production further into the downstream and III) production on the spot. In scenario I) microfactories replace large scale production equipment, whereas in scenario III) microfactories produce something in the place of use. In scenario II), microfactories are used to relocate production further downstream in supply chain, down to retailer level, and therefore it fills the gap between manufacturing in factories (scenario I) and in place of use (III). Regardless of the scenario, micro and desktop factories can be used at different levels of automation, ranging from helping human operators to fully automatic lines. Additionally, regardless of the number of companies in the supply chain, the benefits of using micro and desktop manufacturing are still more or less the same. Table 15 and Table 16 below show the above mentioned three scenarios and list several different application areas for micro and desktop equipment that are speculated in literature.

Table 15. Visions for the potential application areas of Microfactories (Nurmi, 2012). Continues in the following table.

<table>
<tr><td colspan="5">I. Traditional supply chain</td></tr>
<tr><td colspan="2">A. Processing Industry</td><td colspan="3">B. Piece Goods Industry</td></tr>
<tr><td colspan="5">Primary reasons to invest on miniature production systems
+ Increasing profitability: cost savings
* Costs of facilities
- Rents or capital costs, heating, air conditioning, illumination etc.
* Clean room investment and maintenance costs
* Costs of flexibility, quality or manual assembly
* Costs of energy
* Costs of material
* Costs of waste and recycling
* Capital costs (set up time, cycle times etc.)
+ Enabling products chrasteristics (fragile products)</td></tr>
<tr><td>1. Raw material production</td><td>2. Material production</td><td>3. Component manufacturing</td><td>4. Assembly</td><td>5. Finishing and inspection</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>* What?
- Testing and analyses on the spot
- Oil-field investigation
* Why?
- Portable test equipment</td><td>* What?
- Medical
- Chemistry
- Low-volume processs industry products
* Processes
- Chemical reactions of dangerous materials
- Micro cultivator
- Drug fabrication and encapsulation</td><td>* What?
- Metal
* E.g. jewellery and watches
- Glass
* E.g. micro-optics
- Plastic
* E.g. hearing aids
- Ceramics
* E.g. dental
- Biodegradables
* E.g. implants
- Silicon
* Semiconductors
* Processes
- Injection moulding
- Machining
- Additive manufacturing
* 3D printing
* Lithography
* How?
- Fabrication in a cleanroom or under special condition
- Combining to 3D printing</td><td>* What?
- Portable devices
- Precision mechanics, e.g.
* Watches
* Micro-motors
* Gears
- Micro-optics
- Jewellery
- Life science
- Medical/dental
- Semiconductors
- Sensors
- MEMS products
* Processes
- Pick and place
- Screwing
- Dispensing
- Laser processes
- Ultrasonic welding
- Heat treatment
- Palletizing
* How?
- AAM (Difficult manual operations)
- Parallel/ 3D production layout
- Cleanroom assembly</td><td>* What?
- Small products or components, e.g.
* CE marking
* Optical control of assembly
* Sterilization of medical implants
* Processes
- Marking
* Scratching/ laser
- Coating
* Paint/ UV-printing
- Washing
- Cleaning
- Sterilization
- Optical control
- Packing
- Processes under special condition</td></tr>
</table>

Table 16. Visions for the potential application areas of Microfactories (Nurmi, 2012). Continuation from the previous table.

II. Relocating production further into the downstream			III. On the spot manufacturing	
Primary reasons to invest on miniature production systems + Increasing profitability: cost savings and add-on sales * Capital costs (stock of products and semi-finished products) * Add-on sales - Product customization - Fast delivery + Enabling product chrasteristics (pershable products and groceries)			Primary reasons to invest on miniature production systems + Enabling production and the whole business	
6. Transportation, on the fly/way	7. Storage and wholesaling	8. Retailing	9. Production in place of ordering	10. New applications
				
* What? - Small products having long time of delivery and stabile demand - Pershable products * E.g. grocery * Why? - To shorten delivery - To protect the pershable products	* What? - Small products having modular design and intermediate level of personalization * Why? - Dynamic supply chain and delivery - Wholesale level mass customization	* What? - Small highly personalized products, e.g. * Contact lenses * Watches * Jewellery * Cosmetics * Small sport equipment * Craft shops * Medical * How to presonalize? - Coating *Paint/ UV-printing * E.g. laptops - Marking * Scratching/ laser * E.g. iPods - Final assembly * E.g. glasses - Final design * E.g. custsom-fit sport equipment - Drug dosage and encapsulation	* What? - Exchange parts - Spare parts - Medical products - Small products having critical time of delivery * Why? - No space for factory - No time to deliver - Impossible logistics * Where? - Urban factory - Remoteness * Space * Oceans and air * Researchers' special conditions * Battlefield * The third world * Medical products - Custom implants - Battlefield - Dental - Third world * Drug fabrication * Dosage and encapsulation * Sterilization	* What? - New applications for automation and industrial machinery * Why? - The process is the product (education) - Impossible subcontracting (laboratory) * Where? - Prototyping * In a office (design, engineering or architecture) - Education * At school * At Fablabs - Laboratory automation - Processes inside of industrial and laboratory equipment - Craft shops - At home * Consumers * Communities

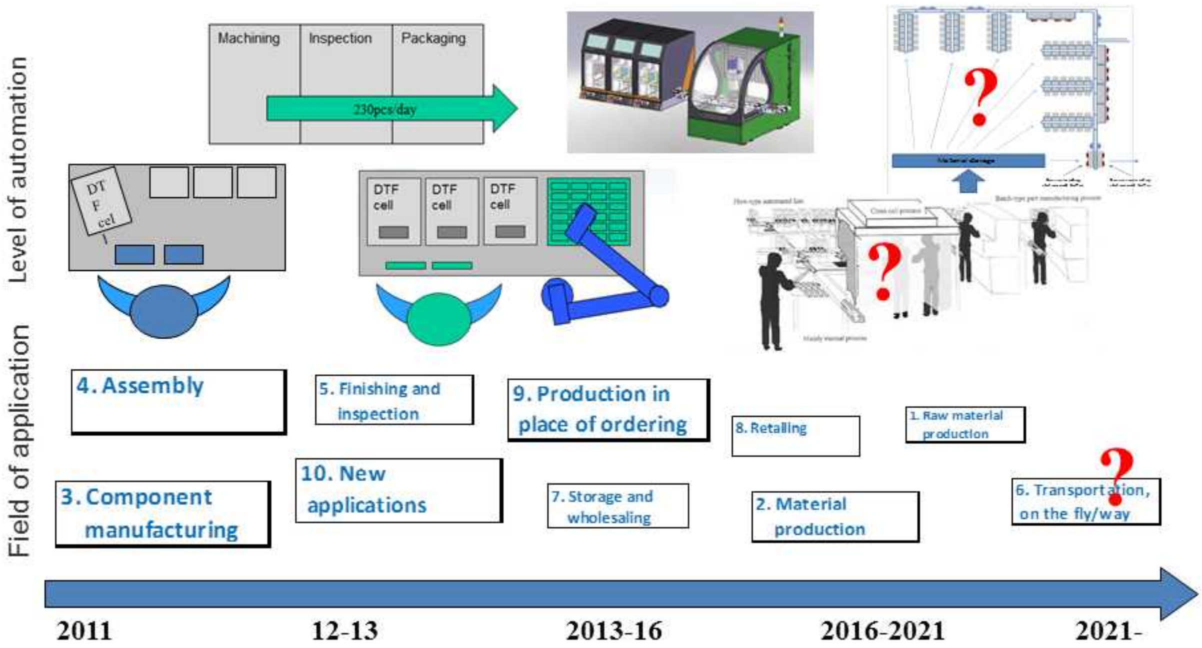

Figure 43. Micro and desktop factory application areas.

Small size and easy portability of desktop size equipment enables, at least in theory, locating manufacturing capacity and organizing logistics completely freely. One could, for example, distribute at least a part of the manufacturing process all the way downstream to shops and retailers. Or one could have a factory in a ship, car or plane to have a mobile factory and do (at least some) manufacturing steps while transporting the raw material and/or parts from place to place. Figure 44 shows different ways to organize and locate production capacity.

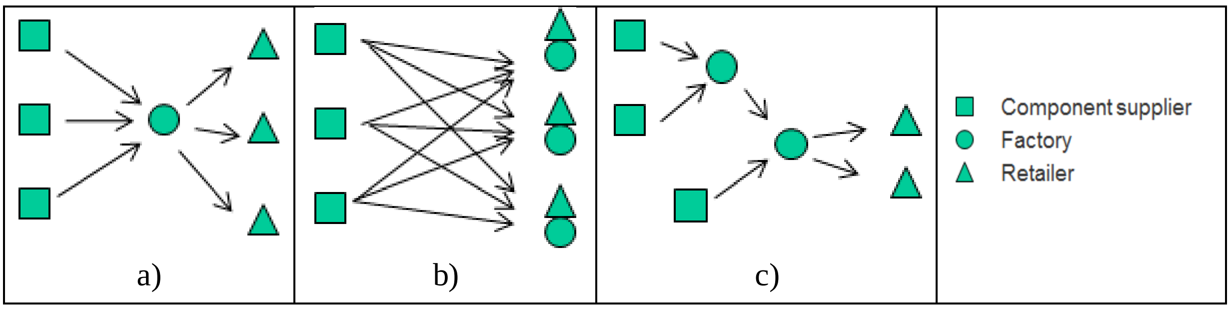

Figure 44. a) Centralized production, b) decentralized production at retailers, and c) decentralized production at "optimal" locations.

Which method and what level of decentralization is best? Unfortunately there are so many variables and, to our knowledge, so little research done on this topic that no clear answer can be given. However, there are basically three scenarios: miniaturization of production equipment in a traditional production and supply chain; relocating production further into the downstream; and production on the spot (as described earlier and suggested in (Tuokko & Nurmi, 2011)), which will be discussed in the following chapters.

6.5.1 Scenario I: Replacing Traditional Large-Scale Equipment with Miniature Production Systems

The first scenario takes place in a traditional production chain (compare Figure 44 a) and c)). In this scenario the traditional and large-scale production machines are replaced and/or supplemented with the micro and desktop production systems. Here, the production process remains the same. Basically, smaller equipment needs smaller factory buildings and consumes less energy and resources or, what seems to be quite important in many cases, enables more production capacity in existing factory buildings. Another potential source for savings is integrating clean rooms into machines which would reduce or eliminate need for traditional large clean rooms.

In general, all products and processes, which fit into the reduced working space, could be produced with a microfactory. However, it does not mean that small machines are needed or that the miniaturization is feasible. Usually there already is large-scale machinery for any given process. A desktop machine or a factory is bought instead if it is better for the application. However, the miniaturized system is likely to be more expensive or a compromise in some way. Therefore, the investment requires other motivation. Requirements for the return of investments depend on the purpose. If the large-scale machinery is replaced with the small machines in order to cut costs, the investment has to yield e.g. 15% annually.

By definition, micro and desktop factories are small and therefore they can save space. Respectively, the floor space reduction can cut costs and therefore enhance efficiency. Because of the small size, the desktop solution might work better for Lean and manual production. According to the CEO of JOT Automation, Mikko Sipilä, in his presentation at TEKES / Tuotantokonseptit seminar in December 2011, Lean requires semi-automatic tools, high re-usability rate and functional testing solutions. Semi-automatic desktop solutions work well for this purpose. (Sipilä, 2011)

The cost reduction factors have been discussed in the literature (e.g. Koelemeijer Chollet et al., 1999; 2003a; 2003b). The space reduction can cut costs of facilities, e.g. rents or capital costs (own factory), as well as costs of heating, air conditioning and illumination. Similarly, microfactories use less energy which cuts costs of energy. Local cleanrooms can decrease cleanroom investments and cut maintenance costs. In addition, microfactories are expected to save material. Therefore, the costs of material, waste and recycling would decrease. With automation assisted manufacturing, microfactories could enhance quality of products. Therefore costs of poor quality would decrease. Finally, microfactories are expected to be more flexible to operate and therefore to have shorter set up times. The flexibility would also cut the capital costs as the shorter set up times enables reduction of the stock of products and semi-finished products.

Microfactories relating to raw material investigation and analyses have been speculated. Because the automation/testing equipment is small and portable, testing and analyses could be automated on the spot. However, applications relating to raw material production will probably not be the first microfactory applications. Same applies for material production and process industry.

In addition, Kawahara et al. (1997) argue that micro and desktop factories could be used as micro chemical plants. Applications include e.g. drug fabrication, micro cultivating and chemical reaction of dangerous materials. Multiple benefits relate to the small reaction space. The reaction starts and ends quickly. Thus, risky exothermic reaction can be safely achieved. In addition, truly homogeneous chemical reaction becomes possible as the concentration differences decrease. (Kawahara et al., 1997) However, microfactories are not suitable for large volumes. For example, instead of pharmaceutics industry, micro cultivation and micro reactors might suite better for laboratory environments. (Härkönen, 2011)

Component and micro part manufacturing was one of the original applications for microfactories. The benefits relate mostly to floor space reduction and relating costs. In addition, the small size machining units enable few additional business models for the equipment providers and subcontractors. Furthermore, the small machines can support Lean and Just-In-Time production as components can be produced on the spot based on requirements. The small components are made of multiple materials: metal (e.g. jewellery, gears and watches), glass (e.g. microscopes, laboratory instruments and contact lenses), plastic (e.g. hearing aids and implants), ceramics (e.g. dental products and moulds), biodegradables (e.g. implants) and silicon (semiconductors, e.g. sensors). Potential miniaturized processes include e.g. injection moulding (e.g. Michaeli et al., 2007; Medical Murray, 2011), machining (Table 3) and additive manufacturing, including 3D printing (Table 13) and lithography. In addition, components can be fabricated in a cleanroom or under a special condition (e.g. Kawahara et al., 1997; Verettas et al., 2005; Kobel & Clavel, 2010).

Assembly operations are other promising application for microfactories. Suitable small-size products include e.g. portable electronic devices (MAG, 2011; JOT Automation, 2011), precision mechanics (e.g. watches, micro-motors and planetary gearheads) (Uusitalo et al., 2004; Järvenpää et al., 2010; CSEM, 2007), micro-optics, life science products (e.g. test kits) and other small medical products, dental products, semiconductors, sensors and measuring devices as well as other MEMS products (Ashida et al., 2010). Suitable miniaturized assembly processes include e.g. pick and place, screwing, dispensing, ultrasonic welding (MAG, 2011; JOT Automation, 2011) as well as palletizing (Asyril, 2011a).

Finally, micro and desktop factories could be used for finishing, inspection or packing, as well as for CE marking, visual control of assembly or sterilization of small medical implants. Other miniaturized processes include e.g. marking, laser carving (Heikkilä et al., 2010, p.

121), painting, UV-printing (Tirkkonen, 2011), ultrasonic washing (Heikkilä et al., 2008), cleaning and sterilization. In addition, a microfactory with a cleanroom enables processes under special conditions. Again, the only restriction is that the small products and components have to fit into the working space. According to Madou and Irvine, Sankyo Seiki made the first commercial equipment for cleaning of micro-parts (Madou & Irvine, 2005).

6.5.2 Scenario II: Production Further Into the Downstream

The second scenario is relocating production further into the downstream (compare Figure 44 b). By smaller machinery, some production steps could be relocated to three different phases between a factory and a customer. Firstly, the products could be produced during the transportation, e.g. on a ship or in an aeroplane. Secondly, the products could be personalized at or before the wholesaling level. Thirdly, the personalization could be placed at the retailing level.

First option is a mobile factory that was first introduced by Kawahara et al. (1997). Because of the small machine size, the production system could be integrated e.g. into a car, train, boat or aeroplane. The materials could be loaded into a car and the manufacturing would happen during transportation. In the end, the car could deliver completed products. (Kawahara et al., 1997) Suitable products would be especially small and perishable products having a long time of delivery and a stabile demand. Production during transportation is speculated to shorten delivery times. However, since the duration of actual transportation time (especially air cargo) is usually short compared to actual delivery time, this might not be the case. It is also speculated that the costs of logistics and capital tied to stocks would decrease with mobile factories. On the other hand, production equipment requires space from the transportation vehicle and therefore transportation capacity decreases.

The second option, to relocate production further into the downstream, is to place some production steps between factories and retailers (see Figure 44 c). Production could be placed either in storages or wholesalers. The model would suite well for small products having modular design and an intermediate level of personalization. A company could do it in order to increase wholesale level mass customization, and increase the dynamics of the supply chain and delivery. Smaller production hubs would also help to adjust to a fluctuating demand. In addition, it might enable a higher level of personalization and the customers might choose the product because it is more personalized, causing add-on sales. However, a lot of uncertainty relates to the cost savings. The potential impact on costs of logistics depends highly on the product and the required processes. If part of the assembly process is personalized, the components have to be transported to many locations instead of one factory. As a result, the costs of logistics might even increase. Instead, coating, marking and subtractive/additive manufacturing processes include much less logistics.

The last option is to place part of production at the retailing level, at the level where the products are bought (see Figure 44 b). Kawahara et al. (1997) use term ‘fabrication in a shop’. To sum up, microfactories could be used to personalize, in retailing, level small and highly personalized products such as contact lenses, watches, jewellery, cosmetics, small sport equipment, pharmaceutics and other medical products. Miniaturized personalization processes include painting and UV-printing (e.g. laptops), marking (e.g. jewellery), final assembly (e.g. glasses), machining (e.g. custom-fit sport equipment) and sorting (e.g. drug dosage and encapsulation). There have been also ideas about manufacturing custom-made medical implants in hospital based on computer tomography (CT) or magnetic resonance imaging (MRI) images in order to shorten the surgery time. Sometimes just a few millimeters can make a huge difference in usability. For example, contact lenses, high-end sports gear and physiological instruments are already produced individually for every customer. In fashion industry, it might be just a matter of taste but the individual design and manufacturing does affect the purchase decisions.

However, retail level personalization includes certain limitations and drawbacks. First, the same logistic dilemma relates to retail level as wholesale level. The costs of logistics might increase dramatically through personalization. If assembly process is personalized, the components have to be transported to many locations instead of one factory. Instead, coating, marking and subtractive/additive manufacturing processes are more potential processes. On the other hand, the number of personalizing retailers includes a compromise. Only few customers can be served with few retailers but a large amount of retailers increase costs. In reality, companies might choose to personalize only in large flagship stores for marketing purposes, and centralize the service for other customers. In addition, the retail level customization should relate to some products which can be bought on impulse. If a customer wants to buy a highly personalized product, he or she can usually wait few days to get the product from a factory.

6.5.3 Scenario III: Manufacturing on the Spot - Ubiquitous Manufacturing

The last scenario, on the spot manufacturing, relates to the speculated ‘ubiquitous manufacturing’ (Okazaki, 2010), ‘point-of-need manufacturing’ and ‘decentralized manufacturing’. Products could be produced by microfactories in a place where they are used. On one hand, something can be produced on the spot instead of ordering. On the other hand, ordering is not an alternative in e.g. education or prototyping.

As microfactories are small, they could be used to produce products on-the-spot in various locations. It would be ideal for small products having critical time of delivery, e.g. exchange parts (Kawahara et al., 1997), spare parts (Okazaki, 2010) and medical products (Heikkilä et al., 2008). There are three principal reasons for manufacturing on the spot: no space for a traditional factory (e.g. urban fabrication in a city centre), no time to deliver (e.g. battlefield) or impossible logistics (e.g. isolated places such as oceans or space). Microfactories could be used for fabrication of custom implants (Heikkilä et al., 2008); dental applications (Okazaki, 2010; vhf camfacture, 2010); drug fabrication, dosage and encapsulation; as well as sterilization. Battlefield (King & Jatoi, 2005), trouble spots and the third world are examples of situations where logistics can be problematic.

The US Army has two good examples of point of need processes: Mobile Parts Hospital and the Mobile Army Surgical Hospital (see Figure 45). According to Barkley (2009), the Mobile Parts Hospital (MPH) is a portable replacement part factory. A MPH includes machinery and three machinists. In 2009, US Army had three MPHs in Iraq, Kuwait, and in Afghanistan. Since 2003, more than 100,000 critical parts have been produced at the points of need. The machinists make CAD drawings based on a broken part, drawings and verbal descriptions. When the CAD drawings are approved, a new part is fabricated in few days. Later on, the CAD drawings will be sent to other units. The point of need fabrication can provide huge cost savings. For example, the MPH made a rotor brake seal for an Apache helicopter. Instead of shipping the rotor back to the States, the helicopter could be used within days, and $393,000 was saved. (Barkley, 2009)

Figure 45. US Army Mobile Parts Hospital

Besides replacing orders, on the spot manufacturing includes other applications as well. The applications are mostly new for industrial automation and machinery. The most potential applications are prototyping (e.g. in engineering, design, or architecture office) and educational use. In addition, miniaturized automation could be used in laboratories (e.g. DYNEX Technologies, 2007a, 2007b; BPC BioSede SRL, 2009a, 2009b; Biohit, 2011a, Pfriem et al., 2011) and for processes inside of industrial and laboratory equipment (Eichhorn et al., 2008). Ordering or subcontracting are usually not alternatives since the process is the product (prototyping and education) or subcontracting is impossible (inside a sealed laboratory). Microfactories could be used even for personal fabrication, selling the equipment for consumers and communities. The iModela iM-01 (see Figure 14), an affordable 3D hobby mill designed by Roland DG Corporation, is a good example of home fabrication (Rolanda DG Co., 2011b).

6.6 Production Types

As mentioned earlier, two main development directions for micro and desktop factories are envisioned. The first one is fully automatic production line consisting of small size production cells or modules as shown in Figure 46 below. This would be very similar to the traditional production lines, the main difference being the size of the equipment.

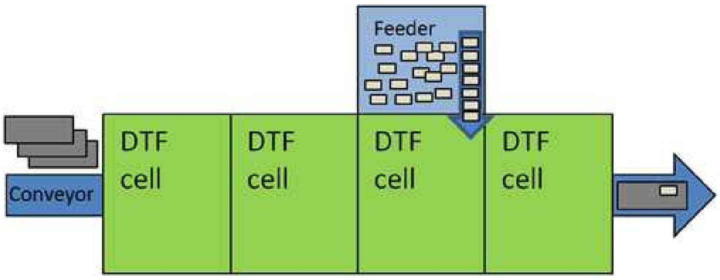

Figure 46. Fully automatic production line consisting of desktop size modules (Nurmi, 2012)

The second main development direction is to use small size equipment for aiding human operators by completing tasks that require great accuracy or speed, are dangerous or are very simple and repetitive and thus boring. In these cases, the desktop size cells could be tele-operated (e.g. manipulation of small parts with very high accuracy), they could be standalone units making a single process (e.g. screwing) or a few process steps (e.g. picking and gluing a component with high accuracy) while the human operator performs more complex operations. See Figure 47.

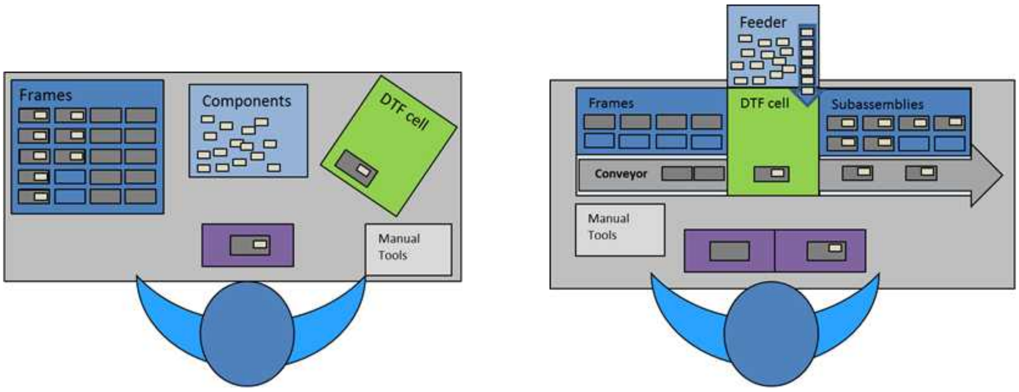

Figure 47. Automation assisted assembly scenarios where one operation is automated one piece at the time (left) or a small batch at the time using trays and feeders (right) (Nurmi, 2012)

After these, the next step might be called robot assisted cell type manufacturing. In this vision, a robot and human operator would share the same working space containing one or more desktop size machines. The robot could aid the operator by performing simple and repetitive tasks (e.g. loading/unloading trays or machines) while the operator performs tasks requiring, for example, dexterous manipulation of flexible or delicate parts. See Figure 48.

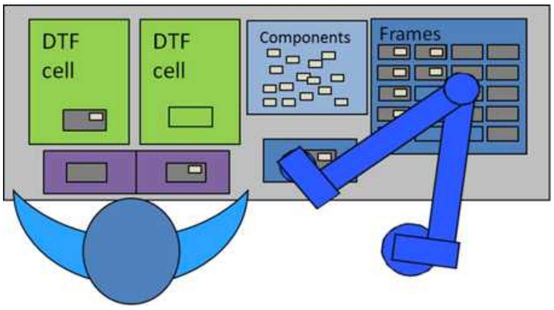

Figure 48. Robot and human sharing the same workspace in desktop production (Nurmi, 2012)

6.7 Vision for Different Actors

This chapter draws the vision of the micro and desktop factories and their usage from perspective of different actors, namely end user, equipment provider and system integrator.

6.7.1 End User Vision

In this context the end user means the user of the micro or desktop factory solution, i.e. a company which uses these solutions to produce its products. In the following is envisioned, listed and shortly discussed the main advantages the end user can gain by implementing micro and desktop factory solutions.

Cost reduction

In order to increase profit, the companies tend to pursue cost reductions. Lean production has proved to be, as pioneered by several Japanese companies, an efficient way to cut costs by reducing waste from different operations. It is seen that more and more end user companies are finally starting to see the benefits of Lean and wish to implement those principles into their production. In addition to the seven types of waste defined by Lean (transportation, inventory, motion, waiting, over-processing, over-production and defects) there are other types of wastes that cause unnecessary costs. These are for example dispensable energy consumption, raw material loss, unnecessarily large production spaces and other, which cause wasted overhead costs. The aim is to get rid of these. With microfactories this all could be possible.

Over specification is one specific type of over-processing waste. The cost of setting too tight specifications or tolerances is getting tremendous large. The specification might be requesting for tens or hundreds times more accurate device than actually is needed, which is just wasted money. When stepping over the specific threshold levels (e.g. requiring other than standard processes or normal class components), the price can increase exponentially. Also the same can be experienced at process side. Some technology (conventional or innovative) might be rejected just because of too tight specifications. Therefore the end user should focus on setting the specifications at right level for the application process i.e. just enough for fulfilling the process needs. This way the inexpensive micro and desktop machinery could fit into the job even more often.

Coping with environmental regulations

The shift towards sustainable manufacturing with emerging environmental regulations pushes the manufacturers to produce their products in a more environmentally friendly way. This means that new technologies and new ways of operation need to be adopted. Investments into microfactory technology can therefore be easily justified from environmental sustainability point of view.

Attracting new environmentally aware consumers

As micro and desktop factory solutions are expected to reduce energy and material consumption as well as to produce less raw material waste, both directly and indirectly (e.g. facility cooling/heating, cleanroom size) they can be considered as more environmental friendly way of production compared with the traditional size 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 micro and desktop factory solutions can thus offer potential for competitive advantage and attracting new environmentally aware customers.

Variable products - configurable systems

Product variation and customization has become an important factor to win the market shares and cope with the fierce competition in most of the fields. Products’ life cycle and time to market are shortening. Therefore the end users require the production systems to be agile and easily reconfigurable for different product models and volumes. Modular microfactory systems can offer the required reconfigurability.

Moving production to most convenient locations

Desktop size equipment enables (at least in theory) locating and moving production capacity easily to places where it is needed, thus enabling new production and logistic concepts and strategies. These aspects are discussed in more detail in chapters 6.5.2 and 6.5.3. Therefore the manufacturer can freely select the most convenient place to manufacture its products based on the company’s strategy.

6.7.2 System Integrator / Equipment Manufacturer Vision

This chapter focuses on System Integrators and equipment manufacturers and draws the vision of the topics they should concentrate on when developing new technologies. The components and component providers for devices and modules are excluded from this and discussed in the next chapter.

Size of the equipment

Even though the definition of desktop size equipment sets relatively strict limits to the size of the equipment, equipment manufacturer has several questions to consider: What is (are) the "correct" size(s) of equipment they are going to provide? What is optimal for different applications? Where is the optimum considering 1) use of energy and resources, 2) space requirements, 3) usability, 4) cost of going "too small", etc.? There are no clear answers for these questions. Instead, equipment manufacturers have to answer these questions considering the market segments, their customers and application areas they are going to target.

High accuracy machines

The size of the components to be handled is decreasing and, at the same time, required tolerances get tighter. Therefore, in many applications, there is a clear need for high accuracy machines. There are many reasons why simply downscaling existing large scale solutions is not always the best way and, therefore, new novel solutions both in structures, material selections and control algorithms of machines are needed. On the other hand, not all applications require high accuracies. For example, in some cases it might be feasible to use sensor based active guidance and therefore the absolute positioning accuracy is not as important as small resolution of movements and/or relative accuracy.

Machines coping with variation

Future production will often have to cope with increasing number of product variants. The modularity and reconfiguration is always facing the problems at the system/product interface, because it has great diversity and cannot be controlled like the systems internal interfaces. Even though the physical interface with products is problematic, since they are usually different from each other, coping with different products and variants requires that the number of product specific parts, fixtures and tools has to be minimized and/or use of generic tooling. This could be achieved through use of e.g. identification of similar features from operated products and using general grippers and tools: Tools have to be easy and fast to change - even automatically. This also supports the expected higher re-usability rate of automation.

Modular equipment with standard interfaces

One method to cope with product variation, high re-usability rate, short lead times and easy scalability of capacity is to use modular equipment with "standard" interfaces. HW modularity is one way for system integrator to provide standard solutions from design and manufacturing point of view. This will be the base enabler for the faster designs and deliveries and scale of volumes in addition to the requests mentioned at the beginning of this chapter. Even though the interfaces add some additional costs at implementation and platform design, their benefits are multiple ranging from the system clarity and simplification to the separation of designs and components into better understandable and tractable blocks, etc.

Making the hardware modular is one way, but an alternative direction would be to implement modularity by configuration and software while keeping the hardware platform as constant as possible. This might be a good solution for basic applications where the same (modular) hardware platform can be used for different cases with minimum case specific changes. Even the end user could configure the equipment to perform the needed operations. This would enable fast delivery and ramp-up times and, hopefully, lower prices. In addition, “standard” hardware platforms could enable production related “application stores” (similar to mobile platforms) where external developers could develop and sell software/applications/configuration settings for common production HW platforms. This could be opening new tracks. The software developing community, with a good set of applications, may promote and rise ones interest on specific hardware or hardware platform. This scenario could be easily true for home/hobby manufacturing environments.

However, having a “standard” hardware platform with a wide range of functionality might be sometimes problematic, because the cost of non-used functions (unnecessary interfaces and process capabilities or functions, like clean room or extra manipulator degrees-of-freedom) might rise too much. This cost rise can be compensated with scale of volumes. Another issue is raised by the system/product interface (See ch. 6.7.2: *Machines coping with variation*). In addition, more challenging applications or high efficiency expectations will require tailor made equipment also in the future.

Regardless of the method and level of modularity, standard interfaces both at hardware and software level would make the life of end users, equipment manufacturers and component providers much easier.

Reconfigurable systems

In order to respond quickly and efficiently to the customer demands, one strategy could be to utilize reconfiguration, which is achieved through modularisation (See previous two paragraphs). This all bases on modular system or platform, which needs to exist beforehand. There exists at least three different kinds of vision options how to benefit on this: 1) Reconfiguration by the end-user, 2) reconfiguration by system integrator or 3) internal reconfiguration.

At the latter one, the system is modulated by the integrator and they have all control over the interfaces and modules. The architecture and interfaces can be private, and module is not necessary the same with physical modules, but can be smaller (i.e. a component can be a composition of design modules, which is detachable afterwards). The system integrator can quickly provide tailored solutions for their customers, from a set of readymade modules and/or utilise existing designs. This gives them advantage in competition comparing to others, as the supplier do not need to design and implement all from the scratch and they already have some tested and proven modules available. However, from end user point of view the solution does not differ from custom designed application.

The second option offers some interchangeability inside and between systems. The module interfaces and architectures are well recognised and there are more than one company providing modules for the system. The control over the system changes is on the system integrator. This is normally the case when hardware is changed to another and integrated system needs to be tested before acceptance. The system-product interface often requires customisation, which leads to this model. This is widely used model in industry today. The implementation level varies.

The first option is mainly a special case of the previous, where the end user is making the changes instead of the system integrator. The change is usually performed at the SW level and no hardware reconfiguration is needed (See ch. 6.7.2: *Modular equipment with standard interfaces*). Even the modular reconfigurable hardware platforms enable this kind of model also at the hardware level. The change could be minor (recipe or parameters) or major (functionality of the module is changed). In case of hardware level changes, there should exist advanced tools supporting the configuration change process. This could mean guide and support system for operators or automatically configurable system modules. The latter one is requiring more research and development efforts and can be taken as interesting and possible future solution.

Even if the system would be created from a modular platform, there exist specific needs in every application. We think that modular reconfigurable system could be beneficial even if about 50-75% of cases could be covered by reconfigurable platform, sometimes even less, and rest is handled with custom designed solutions. The system integrator may then focus better on the special cases that require more (performance, accuracy, etc.) and cannot be done with standard solution. In such cases the *internal reconfiguration* may play a role. The special solution, which may not necessarily be automation, can be also human operator.

Semi-automation

In addition to fully automated desktop size production systems, there is a strong trend towards human assisted semi-automation - or automation assisting human operators. This leads to a solution, where automation is used for tasks, which require high accuracy, high quality and/or short tact time, while operator is making other assembly and manufacturing operations in addition to machine serving. This means that educational and professional level of operators might be quite modest. This will put great demands on the ease-of-use of the equipment and user interface design. Other aspects include safety related issues as the equipment might be working in the same space as humans.

Usability of the systems

Unavailability of trained work force creates needs for easy to operate equipment and simple and intuitive user interfaces. Equipment manufacturers should also consider implementing different kind of Poka-yoke mechanisms (Liker, 2004) to prevent errors and/or alert operators about errors as soon as they occur.

The small size of desktop equipment creates some additional challenges. For example, visibility to inside the equipment to the actual process might be very limited. In such cases, visualising the process and work area to the operator in some way might be necessary. Other example is that due to the small size of equipment, integrating a display and buttons to the equipment might not be feasible. In such cases, using a mobile device to access and control, not only one but multiple, devices is a good alternative. Also the ease of service operations has to be considered. Luckily, modular structure might be helpful since it allows replacing the broken module and conducting service operations off-line.

Advanced sensors

Increasing demands for quality, functional testing and product tracking create needs for advanced sensing technologies such as vision (both visible and non-visible wavelengths, 2D and 3D) and maybe force/tactile sensing. Regardless of the sensing method, finding and integrating sensors to small machines is challenging. Equally challenging is to efficiently analyse the measurement data and to make decisions and/or simple recommendations that will keep production running smoothly and quality at the expected level.

Cabling

Other issue that is often problematic with small devices is cabling, especially with moving parts. The connectors and wire diameters are also small with tiny components and mechanical stress breaks them easily. Electrically and mechanically shielded cables are needed for protection from electromagnetic disturbances, but they are usually too thick and stiff to be easily used in small size machines. Other problem is the sheer number of cables needed when using several sensors and actuators in small spaces.

First solution to this problem is to reduce the number of signals and cables to minimum: power supply and some serial bus based communication method (and in some cases even these can be combined as has been done in Power-over-Ethernet used in many modern machine vision cameras). Better integration of components is also a step to this direction. Integrating of motor, encoder, amplifier and controller into same package does the same. The outer cabling interface is reduced as the feedback signals and e.g. commutation is not getting out of the box. Second step or solution is to use miniaturised flat cables with only the necessary amount of lines and with mini size connectors.

Availability of feasible components

Sometimes there is no feasible component available at least for a competitive price. Here 'feasible' means that the feature set is not too wide for requirements, all important features are present, component size is not too large for available space, and all of the previous combined with affordable price. Even if there are high risks and costs of own development merged with distribution and maintenance, one might see this as a beneficial route. Sometimes this is even necessary if a suitable component just does not exist and it cannot be replaced by e.g. redesign. Sometimes a company might use this as tool for Intellectual Property (IP) protection of their products. Alternative for own development work is to create partnerships with other companies having the know-how and resources for developing the missing pieces (see also 6.7.3: *Partnership*).

6.7.3 Component Provider Vision

This chapter provides our vision for component manufacturers' point of view. It discusses the topics that the component providers should consider in their development actions in order to benefit from the emergence of micro and desktop factories.

Answer to the increased demand of small sized components

Desktop size equipment seems to be gaining acceptance and popularity and therefore there will be an increasing demand for small size components of every type. However, since the field is new, there are several unknown factors, such as: What features and functionality is needed? What is the correct level of integration? What are the interfaces and where they should be located? What is "small enough" and what is too small? When answering these questions, important things to keep in mind are the expected ease of use (both from the end user and from system integrator point-of-view) and cost efficiency.

Since the field of desktop manufacturing is new, there are only a limited number of component suppliers. Therefore competition on this field is currently limited. However, system integrators and end users are looking for a very cost efficient pricing.

Partnerships

High level of integration is one way to build a lot of functionality into small size at competitive price. However, taking too big steps at time causes high risks, for example, by integrating lots of electronics and software into product that has previously been purely mechanical component. In addition, some system integrators do not want to rely on a single (or few) external component providers, but choose to make their own components. Reasons for own component development could be lack of availability of feasible components with low price. The mismatch may come from the physical size and shape or set of available features and functions. The problem could be also that there are just too many unnecessary functions in the component. This will lead to need for self-developed, simplified and differently packed component.

On the other hand, gathering necessary information to design and supply useful components, requires that component providers work in close cooperation with both system integrators and end users in order to find out their specific needs. Furthermore, expected high modularity of desktop equipment requires compatible components that are easy to integrate.

For all these reasons, component providers should prepare to create partnerships with (selected) system integrators and other component providers while also being in close cooperation with the end users. On the other hand, tight partnerships and using external resources and expertise can cause a major risk.

Light-weight components

Due to size limitations, also the actuators used in desktop size equipment are small and therefore the generated forces and torques are smaller. However, high accelerations are needed to perform the fast movements. Minimising the weight of the components is one solution to this problem. However, while minimising the weight, designers have to keep mechanical properties such as strength, stiffness and vibration tolerance/damping at required level. Novel structures and material selections are needed to achieve these goals.

Joint vision with system integrators

Many of the statements made in chapter 6.7.2 are applicable also for the component provider, after some filtering from component provider's point of view. Especially points made and issues related for size of component/equipment, cabling, accuracy, advances sensors, system-product interface and modularity.

6.7.3.1 Development trends in Machine Vision

This chapter is included for several reasons: Firstly, visual inspections are and will be important especially in desktop manufacturing, mainly because of small details and high speeds involved. Second, and the main reason, is that in machine vision world there already are similar trends that we expect to see also in desktop manufacturing field: decreasing size, increasing level of integration and "built-in intelligence", easier to use systems, and also partnerships between software vendors and hardware providers.

The following shortly lists and describes the main development trends in the machine vision area:

More pixels and higher data transfer speeds

The number of pixels on camera detector is increasing steadily. Currently machine vision cameras with 10 MP (e.g. 3840x2748 pixels) and over are available whereas only a few years ago 3 MP was considered as leading edge. Obvious advantage of increasing pixel count is better achievable resolution, but the drawback might be that in order to fully benefit from higher detector resolution, the quality of lens and other optical components must be high quality.In order to keep camera frame rate at reasonable level, the data transfer speed has to increase and USB 3 is one newcomer to data interfaces. Also other interfaces continue to develop.

Smaller size

As shown in Figure 38, Figure 39 and Figure 40 in chapter 5.3.7, the size of the cameras is getting smaller which naturally makes integrating them into machines easier. On the other hand, considering the size of the camera modules used in many hand-held devices, machine vision cameras are still quite big. However, one has to remember that machine vision cameras have additional electronics and connectors that are not necessary in camera modules.

Easier to use

Machine Vision software applications are getting easier to use. Basic applications do not require extensive programming experience; instead they can be often programmed (or actually configured) in-house with minimal training. Also the hardware is getting easier to operate and to integrate with features such as integrated light sources, lenses, and simpler cabling.

More intelligence

Analogue camera interface is now marginal and digital interfaces have become standard. Digital interfaces give more flexibility in resolutions and frame rates. Digital world also enables cameras to complete some tasks that used to load the processing unit (PC) and some completely new tasks. These include operations such as: optimizing data transfer, image size and frame rate; automating some operations (focus, exposure time, white balance, face recognition); etc.

Combining several imaging methods (sensor fusion)

The need for better and more complete data is leading to sensor fusion meaning that data captured with several wavelengths (X-ray, ultraviolet, visible, infrared, thermal, etc.) is combined to one representation.

High Dynamic Range (HDR) imaging

Dynamic range refers to camera’s capability to distinguish both very bright and very dark details from one image. There are several different techniques to implement this and currently increasing number of camera manufacturers are offering better than usual dynamic range.

Colour imaging
Colour images contain more data than grey scale images and therefore the availability of increasing computing power is enabling applications that were not practical even though they were in theory possible. The use of colours is also opening new application fields in new industries.

Decreasing costs
The number of cameras used in a variety of equipment has grown and is growing exponentially. This, and developing manufacturing methods, is decreasing the cost of equipment. On the other hand, easier to use equipment and software are further lowering the costs of purchasing and setting up a machine vision system.

3D applications
Technology and software for 3D applications is getting quite mature and equipment (and software) starts to be available for reasonable price. Now the key question is selecting the most suitable 3D vision method for the application in hand.

6.7.3.2 Development Trends in Controls

This chapter reviews some of the general trends in the control and controllers that we see are affecting the domain of micro and desktop factories. Here we will focus more on the side of hardware issues and trends because, as stated earlier, on the software side the development trends and needs are aligned with macro domain.

Modularity
Modularity will be important at both hardware and software level; at the software side not only in the control applications, but also on (integrated) development environments. The benefits of large sales volumes will emerge when the same general purpose hardware (e.g. controller or IO module) can be utilised in different locations and purposes. Functionality of the part can be changed through software level configuration.

Software and Communication
Uses of component based and object oriented mind sets will become more common. Devices and software blocks are built as configurable components that have clear interfaces and are re-usable. The components can be quickly integrated together as single operating entity solving the given production task. The different pieces of the system are communicating seamlessly with each other.

Object oriented methods and tools are taking over the PLC based (IEC 61131) programming methods, or at least the latter will adopt higher level abstraction methods from the first one. This is partially based on the assumption that more controller hardware will have its’ origin in embedded development.

The importance of interfaces will increase. It can be seen that the system integration will be going more into the direction of configuring and connecting ready modules together. This emphasises the urgent need for clear, well defined and accepted module interfaces. In this approach it will become irrelevant how and with what language the controls of a single module are implemented. Agents and service orientation (SOA and WebServices) are potential approaches.

Size and Power

The miniaturisation trend is also visible at the controllers. The computing power, memory capacity and intelligence level of controllers are increasing while still the hardware is occupying the same or smaller volume than in past. The controller hardware is starting to divide more clearly into two alternative branches. The other is maintaining the same size and form factor as current industrial controllers do. This is somehow natural from usability and practicality point of view. If the size would be smaller, the installation work would be more difficult and e.g. available currents would be limited, because of the use of smaller wire diameters. Another branch is that the size and industrial controller standards are not taken as limiting form factors. This way the designer has more freedom to really utilise the offers of smaller sized electronics components, and this approach is approaching embedded device design. A powerful controller can be packed into much smaller space. However the space limitations are directly affecting the IO connections - general purpose IOs are getting difficult to connect as single wired fashion, but small sized plugs needs to be used.

User Interface and Usability

Simplicity and determinism are expected from the user interface. The applications are getting more complex and intelligent all the time, but part of the intelligence is that these must be hidden from the user - especially from the machine operators. However, the black box approach can often be seen as risk, therefore it is important to market and show the intelligence in a right perspective. The working principles should be revealed. This could be achieved by offering the higher security level users, e.g. maintenance, better and more complete views of the intelligence and let them affect it by their choices.

New and innovative Human Machine Interface (HMI) methods are needed to operate micro and desktop machinery. Touch screens and mobile terminals are industry standard. Often the process is tiny and blocked from the direct sight. In such cases the vision or visualisation aids are helpful. However, new methods would help on normal machine operation. These could be things like teaching by direct interaction, gesture control, haptic/touch, tele-operation (e.g. surgery), etc. In traditional production related fields the culture is expecting some well-known ways to interact, but on new areas such as laboratory automation or biomedical sector, the working methods are not yet stabilised and conservative, which offers fruitful grounds for openly adopting new methods. Also at these domains the operators' educational level is higher, which could affect the matter.

Special attention needs to be placed on designing the system and module concept and architecture so that the process can be easily accessed and observed by the operators. This is especially tricky when the devices are getting tiny and small and limited workspace needs to be utilised in the most effective way. Often this leads to a solution that the workspace is surrounded by processing instruments. Feeding the material in and out needs to be arranged as well.

6.8 Business Models for System Integrators and Equipment Providers

This chapter is based on Anssi Nurmi's Master of Science thesis (Nurmi, 2012) and it discusses business models for equipment providers. By definition, micro and desktop production systems are small and portable. In addition, they represent a new technology on the market. The main question is: How does small size and portability benefit the equipment providers? In conclusion, the technological change provides few positive aspects and potential market segments.

The ideas presented here are largely based on interviews and presentations of several companies: Codourey, 2011; Hériban, 2011; Härkönen, 2011; Kauppi, 2011; Luotonen, 2011; Sipilä, 2011; Zott, 2011.

Other interviews (not mentioned as sources below): Festo AG and Festo Oy (Hanisch, Kenttämies), Bioretec (Heino), Helsinki Haclab (Heurlin), Master Automation Group (Hirvonen), KIT (Hofmann), EPFL/LSRO (Kobel), Fastems (Laitinen), VTT (Marstio, Salmi), Vaisala (Pietari), Suunto (Suominen), Verkkokauppa.com (Tirkkonen). All interviews were done during summer and fall 2011.

6.8.1 Small-size Automation Cells

It appears that the compatibility to Lean and manual production might be one of the primary benefits of miniature production systems. According to the CEO of JOT Automation, Mikko Sipilä, "next coming of lean assembly" is one of the major drivers for automation in the 21st century. Components and tolerances are becoming smaller and products have more variants. Production systems require shorter lead times, increased tracking and higher level of scalability. In addition, the role of China is changing. Because of e.g. salary increases and quality requirements, companies are investing in automation in China as well. Because of pressures for stronger Yuan, some of the production might be moving back to Mexico, USA and Europe. Lean requires semi-automatic tools, high re-usability rate and functional testing solutions. Semi-automatic desktop solutions work well for this purpose. (Sipilä, 2011)

Lean and Agile manufacturers are a potential customer segment for microfactories, but it is not easy for the automation providers. As discussed in the sub-section 6.2, Lean production has relative different requirements and evaluation criteria for production machines (see 6.2 and Table 3.2). For example, the reliability is important for traditional mass production as the production volumes are usually huge. However, there are safety stocks in case of breakdown. On contrary, Lean tends to favour robust and thoroughly tested technologies by offset. In case of a breakdown, there are no (or small) safety stocks. In addition, automated quality control systems, e.g. Jidoka and Andon, stop the process for sure.

Manufacturers with fully utilized factory utilities and increasing demands face the problem of a huge step cost if new factory floor space has to be acquired. In that case staying in the current space with usually quite low fixed costs (€/m2), moving to miniaturized production systems might offer a major competitive advantage. Therefore even if the smaller option is more expensive, it might be selected because it fits better into factory layout.

6.8.2 Small-size Machining Units

As Kalle Härkönen (2011) stated, the small-size of the machining units might enable new charging/business models, e.g. leasing, tie-up sales and capacity sales. Small machines can be carried e.g. with a pallet jack, and the space at customer’s premises does not require any preparations. (Härkönen, 2011) The business model can be anything between direct sales, leasing and package deals. Leasing can be sold with different names as well. For example, high-end digital backs for studio cameras are sold with “capital insurances”. In other words, the first digital back costs the full price. If the customer updates the digital back within given time period, the provider recompenses a certain percentage of the original selling price. For example, 70% of the price will be recompensed if the customer updates the digital back within two years. The same model could be applied for production machinery as well. As the miniature production systems are new, customers are more likely to accept the new charging models.

Any company providing small-size machining units could provide free or inexpensive machines for the customers and charge the use. It is kind of leasing, but it enables these companies to move the machine elsewhere if needed. Charging is only a matter of a contract, e.g. €/hours, €/working hours or €/product. Depending on a customer and the contract, an employee could be provided as well. The model decreases the buying decision. Investments include always risk and large investments might be frightening for companies. In addition, many small and medium size companies do not evaluate the investments broadly enough. It is therefore easier to justify cash flow financing. Furthermore, buyer’s shifting costs increase. The machine at customer’s premises binds the customer. It becomes more difficult to change the provider.

On the other hand, the small size enables capacity sales, i.e. the machines lay at provider’s premises and only capacity is sold. As the machines are small, more machines can be placed at the provider’s premises. Seppo Kauppi (2011) describes that Wegera is providing already such service. Customer can order instant machining services for monthly payment. (Kauppi, 2011) In addition, the provider could have multiple machines on stock and provide a service of capacity scaling. In this case, the provider would adjust the amount of machines, either in customer’s or provider’s premises, based on how much capacity the customer needs. Okazaki (2010b) also refers to similar business model “delivery service of machine tools”. However, both the business models, tie up sales and capacity sales, increase capital requirements, and thus marginal utilities have to be counted.

6.8.3 Small-Size Equipment for Non-Manufacturing Use

In the non-manufacturing market segment, the small size of machinery can be a major competitive advantage as well. The non-manufacturing environments, e.g. educating in classrooms (e.g. Techsoft UK, 2010a, 2010b; Rolanda DG, 2011a, 2011b); prototyping in engineering, design and architecture offices (e.g. 2BOT physical Modeling Technologies, 2010; Dimension, 2010; Objet, 2010a, 2010b, 2011); and automating laboratory and analysis processes in laboratories (e.g. DYNEX Technologies, 2007a, 2007b; BPC BioSede SRL, 2009a, 2009b; Biohit, 2011a, Pfriem et al., 2011), are not build for heavy and large-scale machinery. In addition, there are no direct substitutes for the use. If, for example, an engineering company wants to buy a CNC machine for prototyping in a small office, the large and heavy machines are not reasonable options. Seppo Kauppi (2011) evaluates that the non-manufacturing customer segment will be an important market for Wegera’s product Kolibri. (Kauppi, 2011)

However, retail level product customization has a different setting. For a retailer, it is important to own the machine only if the products which can be bought on impulse. If a customer wants to buy a highly personalized product, he or she can usually wait few days to get the product from a factory. Therefore, the retailer can substitute the production by ordering the product from a factory.

Personal fabrication includes a different setting. If a customer is using the machine only because of pure pleasure, the process is more important than the product. Therefore, it is not substituted easily. However, if a consumer produced utility articles for himself, there is always an option to buy the component elsewhere. According to the authors’ observations in the Helsinki Hacklab, designing the complete system is the main thing for the hobbyists. In addition, it appears that home fabrication will be still a small niche for many years to come. The desktop-size hobby 3D printers have gained more popularity. Users are designing new objects to print and sharing them online (Thingiverse, 2011). Therefore, the industry has strong network effect and the critical mass might be already obtained. It is possible that desktop-size machining units will gain more popularity in the future as well.

6.8.4 Subcontracting with Small-Size Equipment

Finally the small size and modularity of microfactories might enable some new business models for subcontractors. For example, a subcontractor or a contract manufacturer can acquire a stock of multiple small-size process modules. Based on orders, different production lines can be built out of the modules and more customers can be served. Because of the small size, more modules fit into the space. The contract manufacturer might own the equipment or then he might have a subcontractor owning and leasing the equipment. Apparently, some Japanese manufacturers have used microfactories for this purpose (see Endo, 2010). Seppo Kauppi (2011) states, that subcontracting is excellent counterbalance for machine development. Subcontracting can provide parts for the machines, and the machines can be tested in own production. (Kauppi, 2011)

In addition, the small size of machinery can enable a portable maintenance service. As described in the sub-section 6.5.3, US Army has Mobile Parts Hospitals (MPHs) for replacement part fabrication (Okazaki et. al., 2001). A similar model could be expanded into other industries as well. A company could provide spare parts for factories and other machines. Okazaki (2010) states, that the spare part production is a potential application.

7 Strategy for Future Desktop Manufacturing

This chapter gives rough guidelines for the strategy to reach the visions presented in the previous chapter. The strategy is divided to Industrial Strategy and to Research Strategy. We, as a research unit, focused more on the Research Strategy and only give some rough ideas and guidelines for the industrial sector.

To summarise, the basic guidelines for different actors are:

- Everyone: Push the desktop ideology and awareness of the technology and its possibilities. Market and be present at events where potential new fields get together. Tell what is available and what is needed.
- End users: Specify and determine what is needed. Be brave to try out new ways of doing things.
- System providers / integrators: Organize own operations and product portfolios so that supplying equipment fulfilling end user specifications can be done profitably.
- Component providers: Design and supply components which are cost-efficient and easy to integrate to and to take into use in desktop scale equipment.
- Academia: Look further into future, support industrial sector in their shorter term development work and act as a facilitator for cooperation between different parties.

The following chapters give slightly more detailed bases for forming the strategies for the same industrial actor groups as were used in the Vision chapter. A more detailed strategy, or actually a list of things to do, is presented for the research units.

7.1 Industrial Strategy

This chapter presents ideas for forming strategies for the same industrial actor groups as were used in the Vision chapter 6.7.

7.1.1 End User Strategy

As the availability and maturity of the microfactory solutions is not yet good enough, the end users need to push the component and system providers into that direction. The end users need to advertise their needs, requirements and visions to make the vendors more aware of the potential market opportunities of micro and desktop factory solutions. Special attention must be placed to the system definition and request in quotation phases, when defining tact and change times and the level of flexibility for the machine to be purchased.

Due to the ever shortening lifecycles of the products the reusability and reconfigurability of the systems and system components need to be increased. The “use and dispose” method is not anymore feasible. The key question remains “How to prepare for uncertainty and requirements of future?” This requirement needs actions from the technology providers, but also from the end users side.

Necessary short product change times by (often non-skilled) operators require easy to use machines. Demand of remote or offline programmability of the machines and actions related to easy transfer of the recipes or programs between the machines makes it possible to increase the utilization rate.

The end users should be willing to learn more about the configuration, reconfiguration and adaptation of the systems in order to be able to make the modifications by themselves. And the system and its architecture should be capable of addressing the uncertainty aspect by preparation to change. However, in most of the cases the end user is not willing to pay extra for this.

7.1.2 System Integrator / Equipment Manufacturer Strategy

The main focus for system integrators should be designing equipment that, as standard properties, is easy to use and enables fast product changes but is still profitable. Additional effort needs to be exerted to push this new technology to potential users in a variety of application fields.

Different aspects that should be considered:

- **Implementation strategies:** Start from easy processes and applications and apply the gained knowhow to more difficult cases even though immediate sales are not expected. After gaining enough experience company can offer a desktop size machine as an alternative for larger machines in specific applications. When more and more companies gain experience in desktop technology and start to offer them to end users, they become a realistic alternative to the end users. This increases awareness about desktop technology, which then increases the demand.
    - **Own development work:** Can be used for Intellectual Property (IP) protection purposes and/or increasing competitiveness of a company. Naturally careful analyses are needed to decide, which parts are so important that they are worth of own development process and related risks. Involves high development costs but production volumes will bring down the unit costs. The unit cost might be reduced as the product fulfils only the exact need. However, are the developed products and solutions general enough to be used in several places (relating to the production volumes)? Also organizing support for the developed products over time will add costs.
    - **Using ready off-the-self components:** Initial costs are naturally lower, but then one depends on others, who might have issues with, for example, quality,

availability and delivery of goods. You might also be paying for over capacity and unnecessary features while possibly missing some advantageous features.

    - **Using bus systems:** This makes integration easier by reducing the number of needed cables, directs to better modularity of system, enabling easier configuration of modules and increases the re-use of components in parallel and sequential designs.
- **Desktop equipment as a tool or a component:** At least part of desktop machines should be considered as components or tools, similar to today's standard industrial robots. These should be ready-to-operate pieces of equipment that are very easy to configure and tune for different products and production scenarios. This configuration and tuning work should be doable even by end users or, if they do not want to do it, by some company that might specialize in this type of work. This scenario is similar to modern industrial robotics where standard tools (e.g. robots) are used in variety of applications either directly by end users or by system integrators.
    - **Minimising changeover and initial configuration efforts:** Easy and fast configuration for different products requires a strong focus on software development. Thinking about industrial robots; they are relatively easy to configure for a variety of tasks simply by just changing the tool and the software (which is actually quite similar across different robot manufacturers).
    - Extracting this final tuning and configuration work should lower the "base price" of the equipment, as risks and uncertainties covered by the price are reduced. Therefore, if end users are willing to make the configuration on their own, the purchasing price is lower. On the other hand, if end users are not willing to do the configuration, it opens new business possibilities for equipment providers and/or system integrators.

7.1.3 Component Provider Strategy

Desktop technology is still new, rising and developing field with a limited number of companies operating in the field. There are a lot of possibilities but also a lot of challenges. Aspects that component providers should consider:

- Since the field is new, even the current needs and desires are not always clear, not to mention the future expectations. Therefore component providers need to listen carefully what system integrators and end users want from desktop equipment.
- Simply downscaling large scale solutions usually is not the best method. Instead, miniaturization needs to be planned and executed comprehensively.
- Components need to be highly integrated and functionality needs to be packed into small volumes.
- Components need to be user friendly and easy to integrate into machines. All interfaces, and especially software interfaces, need to be as generic as possible.

- Develop new processes and approaches, which have interest for current and new fields.
- Own development work is important since it enables new innovations instead of using the same solutions as others. New and innovative components are easier to sell and self-developed components are usually also cheaper (with large volumes) than components built from off-the-self subcomponents.
- Lot of marketing and presence is needed, especially at events, where potential new fields for micro and desktop factories come together. Showing and demonstrating the existence and applicability of new components and technologies for other sectors will open new opportunities.

7.2 Research Strategy

This chapter introduces a list of topics that universities and other research organisations should, in our opinion, focus on:

- **Bring forward the desktop ideology**; make the current state and future development directions and also emerging possibilities and awaiting benefits of desktop manufacturing known to a wider audience. One convincing way to do this would be to build up a large scale demonstration (or several) showcasing state-of-the-art desktop equipment in selected application areas producing real products. Demonstration(s) should utilize components and equipment from several suppliers.
    - An additional aspect of spreading knowledge about desktop manufacturing is gathering an application-oriented summary of the Asian microfactory research (e.g. which institutes and corporations have worked together with the concepts, which concepts are still under development and which demonstrations have been conducted). All publications are not written in English which complicates the information distribution.
- **Look further into future** and make openings for new development directions and application areas. Universities should develop ideas, operations models, solution templates and technologies that might not have direct and immediate industrial use, but what companies could utilize in longer time perspective in their own development work. Areas that are especially suitable and interesting for universities include:
    - Developing novel desktop size manipulators and their control methods.
    - Developing and utilizing sensors and measurement methods in desktop equipment and also developing methods to utilize measurement data in intelligent ways.
    - Improving the ease-of-use and usability of desktop equipment. This includes, for example, user interface design, visualizing the interiors of desktop equipment (processing area) to operators, methods for easy and fast configuration, perhaps even automatic setting of programs/parameters/recipes, etc.

    - Researching, developing and demonstrating new processes for desktop size equipment.
    - Finding ways to support automation assisted Lean manufacturing using desktop equipment. This includes several aspects such as work organization, ease-of-use, suitable processes for desktop equipment, etc.
    - Investigating how retail and wholesale level personalization relate to the costs of logistic and customer satisfaction. Personalization and customization are possible applications for micro and desktop factories. However, is it feasible or not, is currently unknown.
- **Platforms:** Gather together interested parties from both academia and especially from industry to discuss what is expected from the desktop manufacturing: What companies want to do with the desktop equipment? What the desktop equipment could be used for? Are there any typical applications and what are their performance requirements (speed, accuracy, etc.) that are really needed? The aims of these discussion include, for example:
    - Can we identify properties of one or a few hardware platforms that could be used in basic applications forming a large portion of desktop equipment installations? If yes, then this or these hardware platform(s) could be used in ways discussed in chapter 6.7.2
    - In order to reach the benefits of modular and reusable systems, the modules need to have standard interfaces. Universities cannot tell what these standards should be, but universities can act as facilitator for discussions and work aiming for these.
    - Universities can also act as an unbiased facilitator for enhancing cooperation between different parties and companies from various countries and fields of industries.

8 Conclusion

This document has described and presented the current state of micro and desktop production related development both from academic research and from industrial aspects and also identified the most notable gaps between current research state and industrial needs. It has also envisioned and discussed several different development directions for desktop manufacturing as well as new business opportunities and models for interested companies. Some of these are strong and clearly visible trends whereas some are less likely. The different visions are summarised in the Table 15 and Table 16 in chapter 6.5. This document also gives guidelines for forming strategies for both industrial and academic actors.

To conclude, it seems that there are two main development directions for desktop size production equipment: 1) fully automatic production lines and 2) automation assisted manual work where human operator uses desktop equipment to do things that machines can do better. It also seems that this second direction is the first one to be widely used in industry. In this scenario, desktop equipment is a tool that can be used in a flexible way as a part of (manual) production system following Lean principles even though the equipment itself might not be that flexible.

It also seems that many of the speculated advantages of micro and desktop factories are not proven or are not considered relevant at least at this moment. For example, reduced energy consumption (in some cases down to 1/6th or more as discussed in Figure 11 and Table 7 might not be enough to invest to completely new way of manufacturing products, even though the savings might be considerably larger due to, for example, reduced need for cooling of waste heat. In addition, speculated use of desktop equipment at retailers to personalize customer products might not be feasible due to problems related to logistics. However, one very concise reason for moving to miniaturized production equipment is the lack of available space: For example, a company might need to increase production volume, but is reluctant to make a new big step investment to new infrastructure. In this situation, miniaturized production equipment might enable higher production volumes in a more profitable way.

After envisioning, this document ends with a chapter dealing with Strategy. Since the authors of this document are from academia, this chapter does not give detailed instructions for the industry on how to maximize the benefits of desktop technology. Instead, the chapter gives relatively rough ideas, guidelines and lists things to keep in mind when companies form their own strategies. Since the field is still new and in its first development steps, every one working in this field will benefit from the following actions:

- Making more people aware of the technology and its potential.
- Being brave to try out new ways of doing things. Keeping in mind that simply downscaling existing solutions is not (always) the optimal solution.
- Defining what are the specifications that are needed and what actually is critical.

- Discussing and agreeing on some “standards” or common ways of doing things in order to enable easier modularity, integration and building of multi-vendor systems.

In conclusion, for companies the small size of equipment is not a goal, unlike it might be for academia. What is important for companies are the things that are enabled by the small size of the equipment and the increase in profits this new technology might offer. Authors hope that this document gives readers new ideas that they can use in their own work.

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