Agile Multi-parallel Micro Manufacturing Using a Grid of Equiplets

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Abstract: Unlike manufacturing technology for semiconductors and printed circuit boards, the market for traditional micro assembly lacks a clear public roadmap. More agile manufacturing strategies are needed in an environment in which dealing with change becomes a rule instead of an exception.
In this paper, an attempt is made to bring production with universal micro assembly cells to the next level. This is realised by placing a larger number of cells, called Equiplets, in a “Grid”. Equiplets are compact and low-cost manufacturing platforms that can be reconfigured to a broad number of applications.
Benchmarking Equiplet production has shown reduced time to market and a smooth transition from R&D to Manufacturing. When higher production volumes are needed, more systems can be placed in parallel to meet the manufacturing demand. Costs of product design changes in the later stage of industrialisation have been reduced due to the modular production in grids, which allows the final design freeze to be postponed as late as possible.
The need for invested capital is also pushed backwards accordingly.

Keywords: Grid Manufacturing, Agile, Reconfigurable, Equiplet, Production, Micro, Microsystem, Hybrid, Submissive Product Design

1 Introduction

This research focuses on manufacturing of “Hybrid Microsystems”. Hybrid systems are composed of multiple elements to realise their primary function [1, 2]. Hybrid Microsystems combine multiple functional domains; electronic, mechanical, optical, fluidic or biomedical domains may be included. Though all these different systems share many of the same underlying technologies, the use of micro technology is typically application specific and mainly used for sensors and actuators. This is the reason why Hybrid Microsystems address, a limited number of mass applications excepted, mainly niche markets.

Manufacturing of products for niche markets with numbers in the mid size volume area, in between 10^4-10^7 products annually, is not easy from an efficiency point of view. Dedicated equipment for manufacturing requires high added value at these relatively small production series. Manual production on the other hand strongly relies on labour, which not only is expensive, but also could suffer from quality issues in the high-tech systems markets with its strict quality demands.

2 Manufacturing context for Micro Systems

2.1 Disruptions during ramp up of production in the micro domain

Manufacturing accuracies for assembly operations in the micro domain are constantly evolving. Since micro system manufacturing, in the lower and mid volume domain, is traditionally relying on an extensive amount of manual labour. Supporting assembly tools are typically used, to enable manual workers, in meeting the high accuracies of production. Once fully ramped up, production equipment has been developed and produced. In the move from early production to the ramped up situation, a transition is made from manual production to (semi) automated production. This transition, with large impact on process stability and product quality, is made at some point in which market introduction is at sight, a moment when *invested capital and project risks are rapidly increasing*. Unexpected delays at this point, due to the disruptions of this manufacturing transition, will almost certainly lead to *delayed market introduction* [3].

To avoid the disruptions during ramp-up, applied equipment is preferably to remain unchanged during the transition from R&D to full production. This would be the case if assembly tools during R&D stage, or at least the assembly principle and the conditions under which they are performed, could be reused for semi automated production and later eventually even automated production. Attempts have been made in the past to realise this way of working [4-7].

2.2 Re-configurability

Unlike manufacturing technology for semiconductors and printed circuit boards (PCB), the market for traditional micro assembly lacks a clear public roadmap [8-10]. It is due to the larger variety of processes and the three dimensional characteristics of micro assembly that the technology will not fit into a single manufacturing framework. Due to the high added value of many manufacturing processes, dedicated manufacturing systems have proven to be legitimate in micro manufacturing, even if the manufacturing technology is intrinsically less efficient. On the other hand, many products with lower economic potential don't make it to the market because for this reason. It is the potential of reusing existing manufacturing technology that increases the popularity of flexible equipment. Many suppliers of state of the art equipment offer systems that can be configured in a flexible way to form a dedicated manufacturing system. Problems however occur when these systems have to be converted to changing products. Usually machines are *shipped back* to the factory to be modified (upgraded). This *ceases actual production*, which generally is not acceptable. Therefore the choice is often made to replace the equipment and invest in new systems, leaving the existing systems untouched till the new system is up and running. *If existing equipment would be gradually upgradable, in a true re-configurable sense, investments in equipment could be reduced significantly*.

2.3 Agile manufacturing

The manufacturing environments of present and next decades differ substantially from the past. Technology and consumer markets have become extremely difficult, posing difficulties for the use of traditional top-down planning-based methods for developing manufacturing strategies. More agile manufacturing strategies are needed in an environment in which *dealing with change* becomes *a rule instead of an exception* [11].

Manufacturing Technology is regarded as one of the most important decision areas within the manufacturing management function. Traditionally, management has influenced manufacturing technology to a much greater extent than the other way round. To have a revolutionary manufacturing concept adopted, one of the aims of this manufacturing strategy is to give the organisation *strategic direction with regard to manufacturing issues*. This direction should include technology, people and infrastructure, used in a consistent way, with the strategic objectives of the business [12, 13]. In a future world, where change is a certainty, all company's resources should work together closely to deal with unplanned change. Basically there are only two ways of handling this, *being in control or being flexible*. In this context it is hard to imagine how traditional dedicated equipment would suffice the needs for the future.

2.4 Submissive Product Design

To improve reuse of technology, during the transformation from R&D to full-scale manufacturing, a distinct conformity has to be realised between product design and manufacturing processes [14]. This could lead to more cost effective, gradual and low-threshold industrialisation of micro systems [7, 8]. Basically, this way of working is based on the application of design rules that have been strongly submitted to the available production framework of the manufacturing facility. *Submissive Product Design can be seen as a fortified implementation of DFA* (Design For Assembly) in the micro domain. With Submissive Product Design, *manufacturing technology is unceasingly leading over the Product Design*. If applied conformably through the industrialisation processes, manufacturing complexity will be disentangled into basic assembly operations [8]. This means the use of a larger number of machines with less complex assembly operations. The assembly operations would still require leading edge manufacturing technology, but less assembly research is needed to implement the technology in manufacturing equipment. This paves the opportunities for standardisation, and the much aimed for, reuse of manufacturing technology.

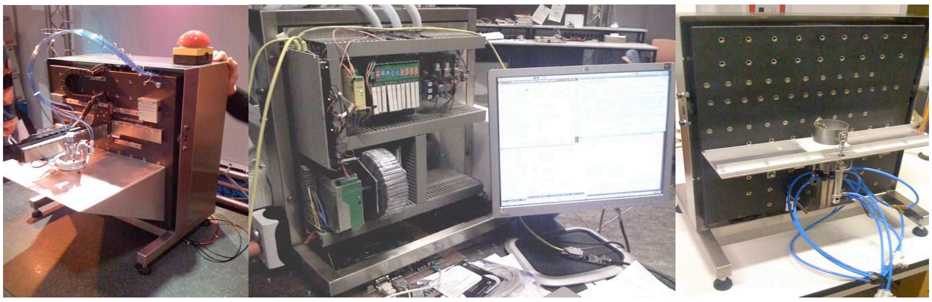
3 Multi Parallel Micro Manufacturing; "Grid Manufacturing"

3.1 Production in the micro domain using "Equiplets"

Typical required accuracies in the micro assembly domain exceed the achievable accuracies of manual labour when performed without any some of instrumentation. With straightforward assembly tools a significant gain in quality of high performance assembly operations can be achieved. The application of manual labour has disadvantages too, mainly in achieving constant & guaranteed accuracies. This preferably would limit manual intervention of operators to the logistical part of the assembly, like handling parts in trays [15, 16]. *The need for increased production conformity, or yield, leads to the implementation of (universal) micro assembly cells*. Much effort has been performed to design these universal assembly cells that meet the agility of human operators [15, 17-27]. Secondly, cost analyses have been performed to justify the application of these cells in an economical context [16, 28, 29]. These efforts have been successful, in a way that universal micro assembly cells can be feasible from a technological and economical perspective. The throughput of these systems however has not exceeded mid-volume production quantities. *In this paper, an attempt is made to bring production with universal micro assembly cells to the next level*. This is done by placing a larger number of cells in a "Grid" (4-100^{+} systems). The universal assembly platforms, which are field reconfigurable, are called "Equiplets". Equiplets are compact and low-cost manufacturing platforms that can be reconfigured to a broad number of applications by adding product dependent tools. These tools are very similar as the tools that are used during R&D and for the manufacturing of pre-production series.

Using Equiplets in production has advantages and drawbacks. These are compared in the next chapter. Two advantages may be seen as the main drivers for applying Equiplets:

- Reduction of risks during Ramp-up. The transition from "R&D-Pilot Production-Automated Production" can be made without disrupting production technology. Optimal consistency through these phases is achieved, minimising risks of non functioning production technology;
- Flexibility gain in the application of production resources. Due to the truly reconfigurable character of Equiplets, and also due to the larger number of Equiplets present in a factory, it is possible to "balance" regular production with the actual production demand. This could be used to balance different production stages of one product, but can also be used to balance production demand over a number of different products to be produced at the same factory.



Picture 1-3: Equiplets in R&D environment. Equiplets are easy to reconfigure due to the modular structure. Ready for production (left) or for a quick test (right), the structure allows experimenting. With an agent based control system, self-learning is an option for the future to further increase accessibility (middle)

3.2 Dynamics of manufacturing in grids

Analogue to “Grid Computing”, where time consuming computer tasks are divided over many computing hardware systems, it is also possible for manufacturing tasks to be distributed over a larger number of production systems. It may be clear that, due to the character of micro assembly, the dynamics of tuning the grid to adapt to changing demand for manufacturing will be of another order than software computing grids. Grid refinement for manufacturing will more likely be on a daily basis (compared to seconds in grid computing). This however is a breakthrough in flexibility compared to dedicated equipment, where substantial equipment upgrades are in the magnitude of months.

Manufacturing tasks are very different from computing tasks in a sense that the adapting the manufacturing grid to start another product cannot always be done in software alone. Note that re-configurability in this context does not mean that the production system is suitable for all thinkable production demands. This is the main reason why manufacturing in grids can only be successful if combined with a solid design strategy like DFA or better “Submissive Product Design”. Although some product switches, especially switches within the same product family, can be done by changing the software jobs alone, it is however most likely to have a combined software and hardware modifications.

Modern adaptive controller architectures, based on software agents, support flexibility and speed of re-configuration, this will be addressed in a future paper.

4 Benchmarking Equiplet production with State of the Art Manufacturing Equipment

In this chapter, Grid Manufacturing with Equiplets is compared with state of the art manufacturing solutions on the following topics:

- Time to market;
- Investment risks;
- Production agility;
- A last topic, to be covered is “Cost Modelling” research. Some basics will be explained in this document, a deeper cost modelling analysis is planned for a near future publication. This will cover issues like cost of ownership, but also up front investing in flexibility that might payback later.

4.1 Time to market, time to volume

Industrialisation of new product developments usually starts with a limited number of R&D prototypes, realised by R&D engineers, to mainly serve for testing of functionality of the product. R&D engineers are usually no experts on manufacturing, which causes the need to optimise the product design for industrialisation. The traditional approach, till some 20 years ago, tended to be fully sequential, but since the 90’s, concurrent engineering strategies have appeared to be more efficient. The overlap of R&D “proof of concept” and “manufacturing engineering” leads to quicker industrialisation, bringing problems due to the up scaling process to the surface in an earlier stage. This while manufacturing investments are still low thus keeping financial risks acceptable. The early involvement of manufacturing engineers leads to more optimised manufacturing processes that are upgradable to reasonable extent. Traditional high volume production with dedicated equipment however, would still need a redefinition of production process and equipment, causing the need for an "equipment feasibility" phase followed by a certain timeframe in which equipment is being engineered and realised (figure 1). Pilot production cannot start before these phases have been completed.

If however the manufacturing of prototypes could be structurally upgraded by the introduction of robotised equipment, manually- or tele-operated in the R&D phase, the technological basis of the production processes would automatically meet the demand for automated manufacturing. In the transition to pilot production, human commands would be gradually replaced by software automation, offering a seamless path to pilot production. As a rule of thumb, it should be envisioned from a manufacturing point of view, that it is not desirable to perform manual operations to prototypes during the R&D phase, but that the operations always should be performed by equipment, or simple reconfigurable equipment, which leads to the use of Equiplets during the entire development and industrialisation phases. Without this dedication the advantages will be gradually reduced to a point in which industrialisation is typically performed sequential, analogue to today's standards.

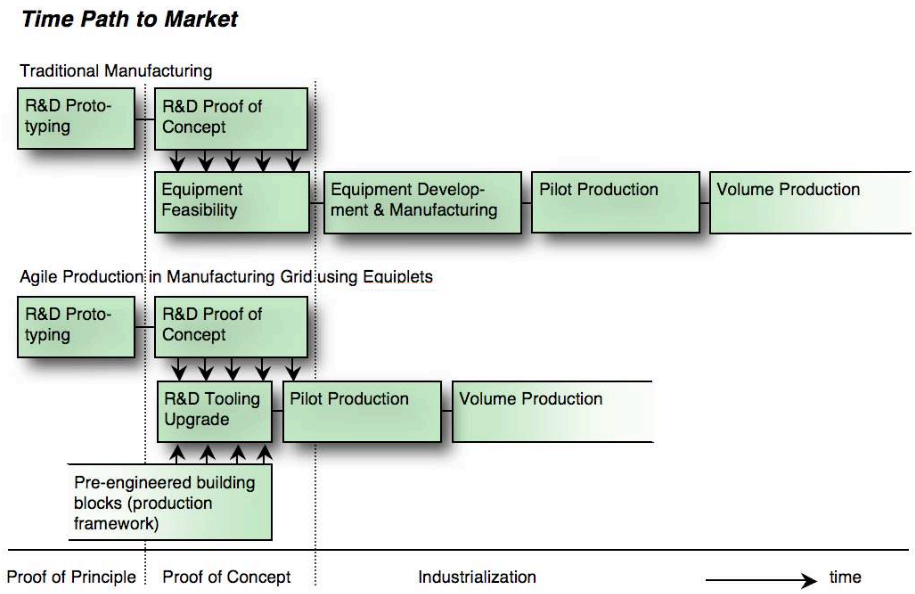


Figure 1: Concurrent development and engineering of High Volume manufacturing processes during the late proof of concept phase. By upgrading well-chosen production technology from R&D to production, a significant time gain can be achieved in bringing new developments to the market.

It will need no explanation that manufacturing in a grid works best when the attitude of R&D engineers is cooperative. As stated in chapter 2, this calls for an increased level of management involvement, which should aim on technology and people as well as the necessary infrastructure. A positive stimulant, to optimise R&D involvement with Equiplets during early phases, is the energy it usually takes to realise prototypes and demonstrators in the early development stage. Especially in the micro domain, this usually absorbs significant amounts of resources. By using robotised equipment in the early stage, the numbers produced could be increased at minimal cost, providing more and also better quality prototypes supporting the research process.

The last point of attention is the process of ramping up to higher volumes. In a traditional way this would be typically done by increasing uptime and the speed of the dedicated production machine. In the case of Equiplet production this is basically the same, under the constraint that the maximum speed of a Equiplet production line will be structurally lower than the well engineered and state-of the art built production machine. This would mean that when the maximum throughput of one production line has been reached, the next step would be to increase the number of production systems that operate in parallel. A major advantage is that the investments in more parallel production lines only has to be sustained when the market demand indeed reaches the next level. If a product appears less successful or has been delayed, according investments can be postponed. If a product is extremely successful, more machines can be configured on fairly short notice, since the complexity of the Equiplets is low due to the decomposition of technology over a larger number of machines. In this way, a manufacturing plant always fits the actual demand (figure 2).

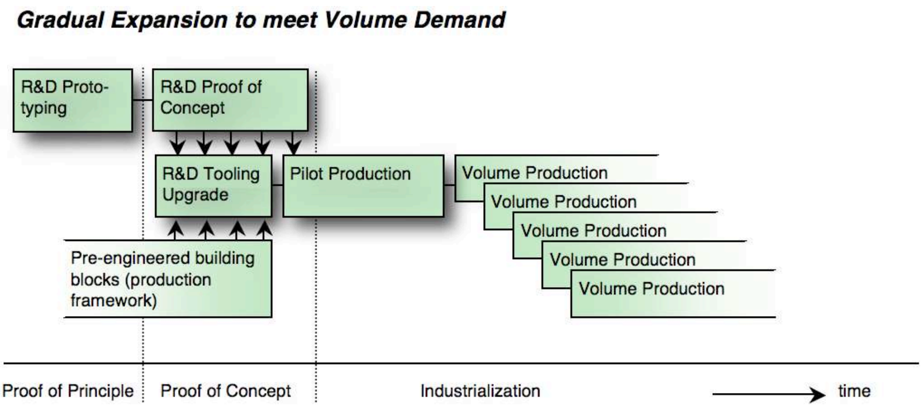


Figure 2: Volume production can be adjusted to market demand, requesting investments tot be done no earlier than revenues start increasing. In this way, investment risks are minimised

4.2 Investment risks

In chapter 2.3 was stated that manufacturing technology is regarded as one of the most important decision areas within the manufacturing management function [11]. Though this true, and there is no shortage on management involvement for manufacturing departments, the moment that the involvement takes place is often timed badly. Management involvement typically increases when the investments are on the urge of rapid increase. This is when R&D is in the Proof of Concept Phase [30] (figure 3). The problem however is that at this point many design issues, and related manufacturing demands, have already been chosen and the costs for industrialisation have been intrinsically determined.

A basic difficulty with manufacturing equipment is that the manufacturing means have to be determined developed and invested up front. With the engineering and realisation of manufacturing equipment, the product design will be frozen except for the exact specified (foreseen) variations within a product family. This is the main reason that the "Cost of Change" for dedicated equipment, as given in figure 3, increases so quickly. Once production has started, problems even get worse, because the manufacturing process has to be shut down to bring product modifications in effect, putting pressure on revenues.

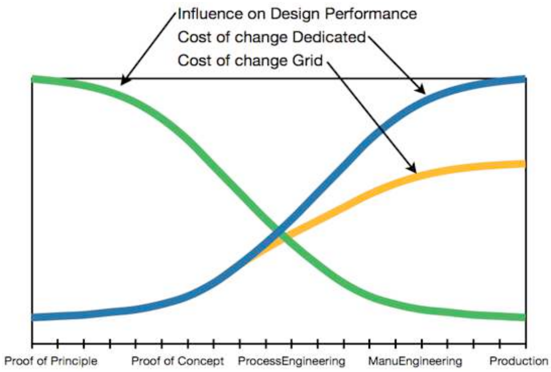


Figure 3: Invested capital leads to increases of the cost for design changes of the product. Typically management involvement increases when facing the Process Engineering stage (halfway the graph). Influences to the Design Performance has drastically reduced

How different will manufacturing be if possible to incorporate a growth strategy with parallel production platforms. With manufacturing in grids this can be achieved after product launch to grow to a certain turnover, but production is still flexible when the product is over the top and markets are slowly shrinking. Manufacturing capacity can be matched to meet product demand in a number of discrete steps. Applying the Equiplet manufacturing strategy will also limit overcapacity on the production floor (see table 1). After reaching the top of sales, production can be reduced using a limited number of production lines. The other manufacturing lines will be reconfigured to support a quick growing new product. In this sense it is constantly possible to tune the actual production to the exact demand.

$$L = \frac{1}{n} \cdot 100\%$$

No of parallel production platforms n	Max overcapacity L
3	33%
4	25%
5	20%
6	17%

Table 1: Overcapacity decreases when the number of parallel production systems grows

4.3 Grid Agility

The manufacturing agility when applying grid manufacturing is improved by two main characteristics:

A. *The Equiplets are reconfigurable, having all advantages of reconfigurable equipment;*

B. *The Grid structure is used to create form-fit production facility. The higher number of systems lead to fairly accurate adjustment to market demand (see table 1).*

Ad A. Reconfigurable equipment combine productivity with acceptable cost in various volume demands [31]. Reconfigurable machines however are not the holy grail of manufacturing automation, but a efficient means for manufacturing products that serve a dynamic market and suffer from short life cycles (i.e. high end electronics, cellphones, PDA, gaming platforms). Once configured reconfigurable equipment acts as a dedicated machine for some amount of time.

Ad B. Manufacturing in Grids will add flexibility, because a larger number of machines will be divided over a number of products to be manufactured. How this works is shown in the next example (table 2):

In February 2010 a new product (I) will be launched that requires two processing operations of type A, three operations of type B and two operations of type C. In February 2010 a total number of eight Equiplets will take care of the production. Two of them will be configured as operation A, three as operation B another two as operation C (2A-3B-2C). A half-year later, market demand has increased, the production scheme now has become 4A-6B-5C. The same month a second product is launched (II). Again some Equiplets are configured to meet production demand. February 2011, the first reconfiguring action takes place. Two Equiplets, configured for operation A, are converted to operation D. Half a year later all Equiplets type A, and one of type B, have been reconfigured tot D. And so on.

	February 2010	August 2010	December 2010	February 2011	August 2011
Product I	2 Type A 3 Type B 2 Type C	4 Type A 6 Type B 5 Type C	5 Type A 7 Type B 7 Type C	3 Type A 4 Type B 3 Type C	
Product II		3 Type B 5 Type C	7 Type B 11 Type C	8 Type B 12 Type C	6 Type B 8 Type C
Product III			1 Type B 1 Type C 1 Type D	4 Type B 4 Type C 5 Type D	9 Type B 10 Type C 12 Type D
Total No of Equiplets	2 Type A 3 Type B 2 Type C	4 Type A 9 Type B 10 Type C	5 Type A 15 Type B 19 Type C 1 Type D	3 Type A 16 Type B 19 Type C 5 Type D	15 Type B 18 Type C 12 Type D
	Total 8	*Total 23*	*Total 40*	*Total 43*	*Total 45*

Table 2: Example of dynamic configuration of a manufacturing grid. Production is expanded to roughly fifty Equiplets in 18 months to meet manufacturing demand for three products.

In this case the factory floor grows to a number of roughly 50 Equiplets that are continuously converted to new production operations to meet the manufacturing demand for each actual product (A to D). Every now and then a machine is converted to another operation, causing minimal downtime, since the rest of the grid continues production. Machines are not necessarily logistically coupled to physical production lines, which is usually not interesting for the micro domain [16]. Adding logistical systems, conveyors, tray handlers etc, could however be economically feasible, especially near completion of the product when physical product volumes increase.

The example shows the excellent flexibility of the manufacturing grid, where transformation from one to another product can take place with minimal downtime. After initial configuration, the advantages get bigger when the reconfiguration takes place, since from that moment on, reuse of technology and investments contributes to more efficient application of resources. Again, the need for an effective DFA strategy should be emphasised. Since quick launch of production, as well as successful reconfiguration, only can succeed in close cooperation with R&D people.

4.4 Cost Modelling

Though in the past some cost modelling on micro production cells has been performed [16, 28, 29] there is no extensive literature on this topic available. Some first facts from literature:

- There is little or no need to invest in the automation of logistics. In view of weight and size it will be more cost effective to have operator bring parts to the machines in containers;
- Components need to be kept in batches, like trays, wafers or SMIF boxes to maintain orientation of products. This suppresses the need for realignment in every station;
- It may be expected that cost models will lead to new design rules for the set-up of micro factories;
- Cycle time remains an important factor, since its reduction directly leads to less equipment on the factory floor;
- Floor space could be a bottleneck. Dedicated equipment with a high engineering level is efficient on floor space. Microsystems manufacturing regularly take place under clean room environments, which lead to high cost of floor space. Though the footprint of the Equiplets will be small, a large number of them will be less efficient in comparison to dedicated machines.

5 Conclusions

The application of dedicated equipment causes disruptions during transformation of the product from R&D to the manufacturing phase. To avoid the disruptions during ramp-up, applied equipment is preferably to remain unchanged during the transition from R&D to full production. This would be the case if assembly tools during R&D stage, or at least the assembly principle and the conditions under which they are performed, could be reused for semi automated production and later eventually even automated production.

Using a DFA strategy, manufacturing complexity will be disentangled into basic assembly operations. These operations can be performed by relatively simple manufacturing platforms. By placing a larger number these platforms in a grid, a flexible manufacturing solution can be realised. The universal assembly platforms are called Equiplets, compact and low-cost manufacturing platforms that can be reconfigured to a broad number of applications by adding product dependent tools. These tools are very similar like the tools that are used during R&D and for the manufacturing of pre-production series. In this way existing R&D equipment is gradually upgradable, in a true re-configurable sense, investments in equipment are reduced significantly.

Especially when more agile manufacturing strategies are needed in an environment in which dealing with change becomes the central point, Equiplets can offer truly reconfigurable manufacturing, adaptable in small discrete steps, accurately matched to actual market demand.

Benchmarking Equiplet production has shown reduced time to market and a smooth transition from R&D to Manufacturing. When higher production volumes are needed, more systems can be placed in parallel to meet the manufacturing demand.

Costs of product design changes in the later stage of industrialisation have been reduced due to the modular production in grids, which allows the final design freeze to be postponed as late as possible. The need for invested capital is also pushed backwards accordingly.

The agility of the grid is unmatched. Reconfiguring machines can be done at a low level, reconfiguration of the Equiplets slows down production only partially. Total production shutdown, standard consequence in case of dedicated production lines, is prevented.

6 Future research

Future research will address a cost model that can be used to estimate industrialisation cost of Equiplet-Grid manufacturing in comparison to dedicated and flexible manufacturing systems.

Secondly the contribution of modern (agent based) controller architectures will be investigated to see if self learning capabilities can further increase the ease of use of Grid Manufacturing with Equiplets, preferably in the most early R&D stage.

7 References

[1] F. W. Kear, *Hybrid assemblies and multichip modules*. New York: Dekker, 1993.

[2] Tichem and Tanase, "A DFA Framework for Hybrid Microsystems," in *IPAS 2008*, Chamonix, 2008.

[3] G. A. Moore, *Inside the Tornado: Strategies for Developing, Leveraging, and Surviving Hypergrowth Markets*: Collins Business, 1995.

[4] Schünemann, Grimme, Irion, Schlenker, Stock, Schäfer, and Rothmaier, "Automatisierte Montage und Justage von Mikrokomponenten," in *wt Werkstattstechnik*. vol. 89, 1999, pp. 159-163.

[5] V. Grosser, H. Reichl, H. Kergel, and M. Schünemann, "A fabrication Framework for Modular Microsystems," in *MST News*, 2000, pp. 4-8.

[6] EUPASS, "EUPASS External Progress Report," in *EUPASS External Newsletter*, 2008.

[7] E. Puik, "A Lower Threshold to the World by Combining a Modular Design Approach and a Matching Production Framework," in *COMS2002* Ypsilanti, USA: Mancef, 2002.

[8] A. Gutierrez, "MEMS/MST Fabrication Technology based on Microbricks: A Strategy for Industry Growth," in *MST News*. vol. 1/99, 1999, pp. 4-8.

[9] Becker, "Micro- and Nanotechnologies for Advanced Packaging," in *mstNews*. vol. 3/05: VDI/VDE/IT, 2005.

[10] Heeren, Salomon, and A. El-Fatatry, "Worldwide Services and Infrastructure for Microproduction," in *mstNews*. vol. 2/04: VDI/VDE/IT, 2004.

[11] A. Gunasekaran and Correa, *Agile Manufacturing as the 21st Century Strategy for Improving Manufacturing Competitiveness*, 2001.

[12] Goldhar and Jelinek, "Plan for Economies of Scope," Harvard business review, pp.141-148., Ed., 1983, pp. 141-148.

[13] Stecke and Raman, "Production Flexibilities and their Impact on Manufacturing Strategy," in *Graduate school of business administration*, U. o. Michigan, Ed.

[14] Salomon and Richardson, "Design for Micro & Nano Manufacture," in *mstNews*. vol. 3/05, 2005.

[15] Hollis and Rizzi, "Agile Assembly Architecture: A Platform Technology," in *ASPE American Society for Precision Engineering* Orlando, Florida, USA, 2004.

[16] Koelemeijer-Chollet, "Cost Modelling of Microassembly," in *International Precision Assembly Seminar 2003* Bad Hofgastein, Austria, 2003.

[17] Mardanov, Seyfried, and Fatikow, "An Automated Assembly System for a Microassembly Station," *Computers in Industry,* vol. 38, pp. 93-102, 1999.

[18] Hollis and Gowdy, "Miniature Factories for Precision Assembly," in *International Workshop on Micro Factories*, Tsukuba, Japan, 1998.

[19] Yang, Gaines, and Nelson, "A Flexible Experimental Workcell for Efficient and Reliable Wafer-Level 3D Microassembly," in *International Conference on Robotics & Automation*, Seoul, Korea, 2001.

[20] F. Fahlbush, Seyfried, Buerkle, "Flexible Microrobotic System MINIMAN: Design, Actuation Principle and Control," in *Advanced Intelligent Mechatronics, IEEE/ASME International Conference* Atlanta, GA, USA, 1999.

[21] Zhou, Aurelian, Chang, Corral, and Koivo, "Microassembly System with Controlled Environment," in *Microrobotics and microassembly*. vol. vol. 4568 Conference No3, Newton , ETATS-UNIS (29/10/2001) 2001, pp. 252-260.

[22] Kim, Kang, Kim, Park, and Park, "Flexible Microassembly System on Hybrid Manipulation Scheme," *The International Journal of Advanced Manufacturing Technology,* vol. Volume 28, pp. 379-386, 2005.

[23] Gaugel, Bengel, and Malthan, "Building a Mini-Assembly System from a Technology Construction Kit," *Assembly Automation,* vol. 24, pp. 43-48, 2004.

[24] Tanaka, "Development of Desktop Machining Microfactory," *Riken Rev J0877A,* vol. 34, pp. 46-49, 2001.

[25] Lauwers, Edmondson, and Hollis, "Progress in Agile Assembly: Minifactory Couriers Based on Free-Roaming Planar Motors," in *4th International Workshop on Microfactories*, Shanghai, China, 2004, pp. 7-10.

[26] Clévy, Hubert, and Chaillet, "Micromanipulation and Micro-Assembly Systems," in *IEEE/RAS International Advanced Robotics Programm, IARP'06* Paris, France, 2006.

[27] Cecil and Gobinath, "Development of a Virtual and Physical Work Cell to Assemble Micro Devices," in *14th International Conference on Flexible Automation and Intelligent Manufacturing. Robotics and Computer-Integrated Manufacturing*, 2004, pp. 431-441

[28] Koelemeijer-Chollet, "Economical Justification of Flexible Microassembly Cells," in *International Symposium on Assembly and Task Planning* Besancon, 2003.

[29] Koelemeijer-Chollet, "A Flexible Microassembly Cell for Smal and Medium Sized Batches," in *Procedings of 33rd International Symposium on Robotics*, 2002.

[30] P. A. Roussel, K. N. Saad, and T. J. Erickson, *Third Generation R & D: Managing the Link to Corporate Strategy*: Harvard Business Press, 1991.

[31] Dashchenko(editor) and Koren, *Reconfigurable Manufacturing Systems and Transformable Factories. General RMS Characteristics. Comparison with Dedicated and Flexible Systems*: Springer, 2006.