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Addressing sustainability and flexibility in manufacturing via smart modular machine tool frames to support sustainable value creation

Bernd Peukert[a*], Stephan Benecke[b], Janire Clavell[b], Sabrina Neugebauer[c], Nils F. Nissen[d], Eckart Uhlmann[a], Klaus-Dieter Lang[bd], Matthias Finkbeiner[c]

[a]*Institute for Machine Tools and Factory Management, Technische Universität Berlin, Germany*
[b]*Research Centre for Microperipheric Technologies, Technische Universität Berlin, Germany*
[c]*Chair of Sustainable Engineering, Technische Universität Berlin, Germany*
[d]*Fraunhofer Institute for Reliability and Microintegration, Berlin, Germany*

* Corresponding author. tel.: +49-30-314-24452; fax: +49-30-314-24456. *E-mail address:* peukert@iwf.tu-berlin.de

Abstract

Sustainability and flexibility are crucial aspects in todays' manufacturing processes. Within this study an innovative approach of modular machine tool frames (MMTF) equipped with micro system technology is presented that aims at enhancing flexibility of mutable production processes. This new approach extends the existing reconfigurable manufacturing systems (RMS). MMTF goes beyond the platform approach via minimizing the machine tool frame parts used for the building block system of manufacturing cells. The concept has been realized by integration of modularized microelectronics and actuators enabling for integrity and accuracy of the machine tool frame.
In this contribution, sustainable hotspots for the production of the MMTF are identified via a tiered life cycle sustainability assessment. From these findings, new approaches are derived that provide for a reasonable usage of mechanical and electronic components in MMTF for sustainable value creation.

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Keywords: modular machine tool frames; micro system technology; life cycle sustainability assessment; sustainable value creation

1. Introduction

Fast responsiveness to unpredictable market changes are a key requirement for staying competitive. After the advent of microprocessors, these market demands steadily led to the development of flexible manufacturing systems and later flexible manufacturing cells (FMS and FMC). This development is an ongoing trend and is still observable in nowadays market situation of machine tools and the general field of manufacturing. In previous publication [1], the authors presented a detailed picture of advances in microsystem technologies along with the improvements in machine tools using achievable machining accuracy as an indicator on a timeline.

The term 'flexibility' is difficult to define and measure. Researchers began with various investigations on this topic in the early 1980s. According to [2], there exist at least 50 different terms for the various types of flexibility. Approaches for the quantification and measurement of flexibility are given in [3], [4] and [5].

Apart from technical performance and flexibility, the establishment of sustainability is of fundamental importance for today´s society as promoted by the Brundtland Commission in 1987 [6]. Therefore, in addition to the solution finding process on the mere technological level, researchers have to consider environmental, social and ecological aspects within the product or process development.

Within this study the approach of reconfigurable and reusable flexible machine tool frames is presented targeting technical flexibility as well as sustainability performance. ITO provides the developing history of modular design for machine tools [9]. Initial concepts of building block systems (BBS) given by [10] and cellular structures made of volumetric primitives given by [11] are purely mechanical solutions for modularization. The development of smart sensors under

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consideration of a form factor compatible with the chosen of modular machine tool frame structures lead to an approach differing from prior research in modular machine tool concepts.

Disturbances, e.g. thermo-mechanically induced stresses, can be compensated with active elements using algorithms evaluating sensing data provided by distributed microsystems. The utilization of lightweight and hence compliant structures in conjunction with active blocks and smart microsystems leads to more flexibility and faster responsiveness on mutable production requirements. This change may also open up new perspectives for improving sustainability of production technology.

1.1. Life cycle sustainability assessment

Life cycle sustainability assessment (LCSA) for measuring impacts affecting environment, society and economy is used to ensure the consideration of sustainability aspects within the development of the introduced modular machine tool frames. The LCSA framework was established taking into account all three dimensions of sustainability, which is essential to display the resulting effects in a holistic way [13]. LCSA consists of a contemporary implementation of life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (SLCA) [14]. Hereby, the assessment of the environmental dimension is the most advanced method, as LCA is a standardized method [15]. The LCC assesses the economic dimension and is relatively new within sustainability assessment [16]. The SLCA has been defined as the technique to assess the positive and negative social impacts along a product´s life cycle [17]. Except LCA, the regarded methods provide some challenges, as the status and inclusion of indicators has not been clarified nor defined in any detail.

To tackle these methodological challenges in connection with LCSA, Neugebauer et al. [18] proposed a Tiered approach including a sustainability footprint. In this contribution, the Tiered approach is followed by addressing impacts of the technology itself, e.g. mechanical elements and microsensors are further investigated. Furthermore, potentials to reduce these initially caused direct impacts on sustainability are discussed by the identification and minimization of hotspots in the production phase of the system design.

1.2. Microsystem enhanced modular machine tool frames

A 3-axis milling machine tool frame is chosen as a use-case. The proposed building set of modular machine tool structures [12] has been used and a methodology for placing wireless sensor nodes in an optimal way has been applied [19] as shown in Fig. 1. The measurement data of the wireless sensor nodes is then used to reconstruct the thermal induced deformations of the tool center point (TCP) as seen in Fig. 1 on the right side.

As boundary conditions for the simulation of temperature fields, a moving heat source is modeled, representing a linear drive in operation. An additional convection condition is applied. The reconstructed displacements are obtained using the temperature data from 10 sensors located as shown in Fig. 1 and an estimator matrix.

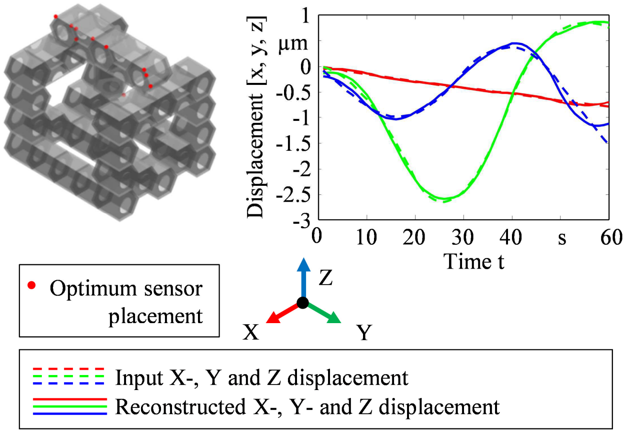

Fig. 1. Optimal sensor placement (left); reconstruction of deviations at tool centre point (right) [19]

The reconstructed displacement values are within 0.5 µm from the finite element (FE) values. Hence, the functional unit which will be evaluated in further sections, consists of 36 hexagonal blocks, 12 half hexagonal blocks and 10 wireless sensor nodes.

2. Assessment of modular machine tool frames (MMTF)

To evaluate the sustainable impacts of the production of modular building set, the according life cycle for the assumed use-case will be analyzed. The half and full hexagons are designed for low weight and high stiffness. Hence, they are designed as shell structures. Both parts share the same manufacturing processes. The production chain is displayed in Fig. 2. In the first step, the raw steel plates are cut by water cutting process. Subsequently, the parts for the blocks are milled, followed by the welding of the building blocks. As welding induces thermal tensions and permanent deformations, the next step is the annealing of the welded structure. The last step is another milling and drilling process to finish the building block. Hereby, the building blocks outer faces are milled to their final shape and the connection holes become drilled.

2.1. Intended assumptions for the manufacturing of the building block system

Regarding the materials and single process steps some assumptions have been made to perform the assessment. For the raw materials, steel needed for the blocks, three main contributors of iron ore on the world market were found, China, Australia and Brazil [20]. In this paper, the country of manufacturing of the modular building blocks is assumed to be Germany. Hence, all calculations are based on the German steel production. According to [21], it is likely that the iron ore is originally mined in Brazil. This assumption will be the basis for the calculations of the sustainability footprint including a fair wage assessment and a carbon footprint according to the Tiered approach in [18].

Accordingly, the energy used for operating the processing machine tools is taken from the German energy grid mix. For the calculation of the length and time of the water cutting process as well as the determination of the offcuts, a rectangular raw steel plate is used. The cutting pieces are aligned in a way that slicing the same edge twice is not necessary. An average cutting length is calculated afterwards by dividing the overall cutting length through the amount of plates used in the above described scenario. The final milling step consists of drilling and finishing of the surfaces. The energy values used for rough and fine cutting of steel are taken from [22].

2.2. Carbon footprint of MMTF

The LCA software GaBi has been used for assessment of the carbon footprint (kg CO_2-eq) for one half and one full hexagonal blocks. The results have been calculated by means of the CML (Centrum voor Milieukunde, University Leiden) characterization method [23].

As formerly described, the frame of the use-case consists of 36 hexagons and 12 half hexagons. The pie diagram presented in Fig. 3 shows the carbon footprint of the different processes involved in the manufacturing process of the blocks. The cutout part of the diagram presents the raw material used within manufacturing. The half hexagon contributes with an overall of 39.58 kg CO_2-eq and the full hexagon with 64.29 kg CO_2-eq.

The raw steel plate production dominates the carbon footprint of the overall MMTF. Second to that, the water cutting process has an impact of about 11% (half hexagonal block) to 16% (hexagonal block). However, the results are obtained by assuming an already filled up closed-circle of lubricant supply with a typical loss of about 30% p.a. The behavior changes when the lubricant has to be completely refilled, leading to a significant increase of carbon footprint of the milling processes by a factor of 150 to 200.

Therefore, further research will focus on a more efficient manufacturing and finishing of the BBS, reducing the material use but also the improvement of process parameters in the water cutting process and milling processes. More resource efficiency could be achieved by taking lightweight design principles into account. In addition, to increase the ecological performance of the structure, more research will be done in connection with the substitution of processes, e.g. introducing casting processes.

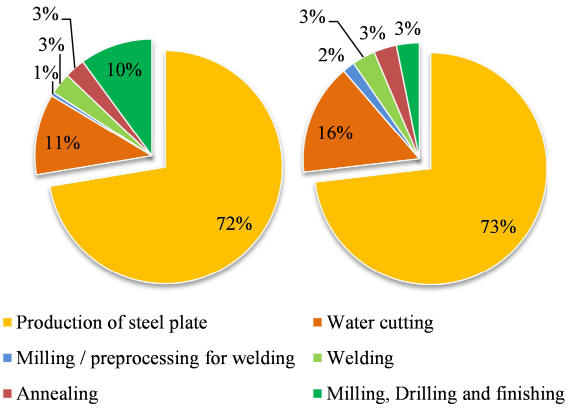

Fig. 3. kg CO_2-eq. of building blocks half hexagon (left) full hexagon (right)

2.3. Fair wage assessment of MMTF

The manufacturing of the modular building blocks involves different trades and disciplines. It is already described, that the iron ores origin is assumed to be Brazil and the production of the steel plates as well as the hexagonal blocks is located in Germany. Therefore, within the Fair wage assessment non-poverty wages, minimum wages and living wages has been considered for the respective group of workers on a country and sector level. The following Tab. 1 gives a summary of the evaluated risks according to the necessary trades.

According to [24], [25], [25], iron ore mining has a low risk of wage below poverty line and wage below minimum wage. There is a slight risk for low-educated workers, who are located on a low hierarchical level, e.g. accommodation jobs in mining. The risks for steel production workers in Germany are also very low. The same holds true for metal workers in Germany performing the necessary milling, welding and drilling operations.

As a conclusion of the social indicator of the first Tier in this SLCA one can say, that from a social point of view the production of modular building blocks in Germany is uncriti-

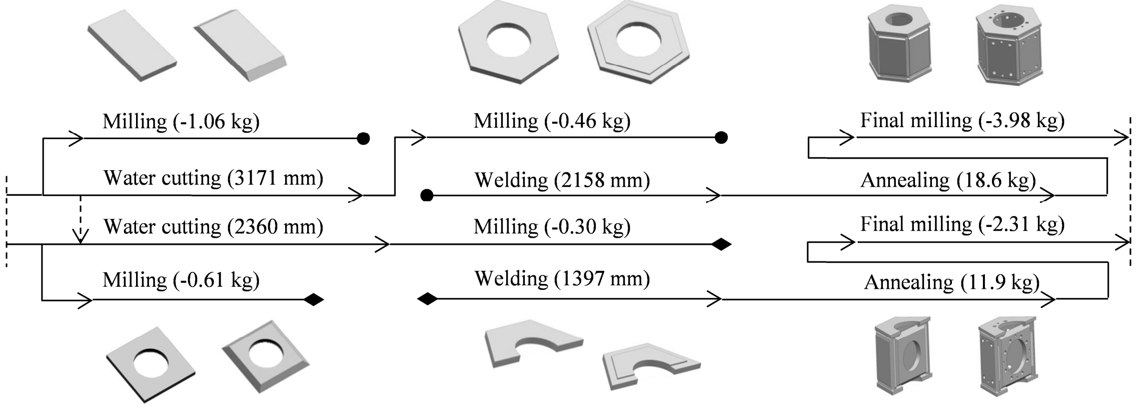

Fig. 2. Process chain for manufacturing of modular building blocks

cal. Nevertheless, further social impacts should be evaluated to reinforce these results.

Tab. 1. Evaluation of the risks of wage below poverty line according to the involved trades

Process	Trade	Risk
Iron ore mining (Brazil)	Accommodation job in mining	medium
	Miner	low
	Mining engineer	very low
	Geologist	very low
	Machine operator	low
Steel production (Germany)	Metal manufacturer	very low
Metal worker (Germany)	Metal former	very low
	Metal worker	very low

2.4. Manufacturing costs

An inherent necessity of lightweight and modular BBS is a need for a higher amount of components to adapt the required machine tools structure. In the use-case described above, 48 blocks are used which make a machine tool of smaller size. Therefore, the manufacturing costs of BBS will be drastically reduced by mass production when progressing further to a concrete market development. Nevertheless, to evaluate the exemplarily manufacturing chain, an evaluation is carried out assuming a small sized production volume. The different processes shown in Fig. 2 are given to German manufacturers; hence the presented estimations are meaningful estimations in terms of calculated costs of the single manufacturing stages. The results are presented in Fig. 4.

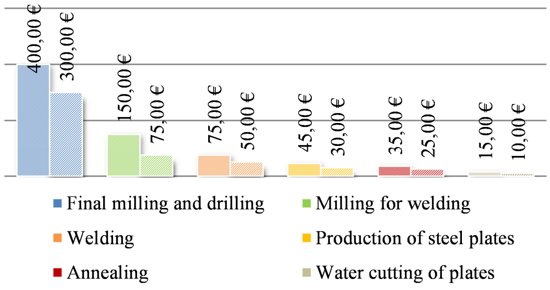

Fig. 4. Manufacturing costs of the building blocks; dotted represent full hexagons, dashed represent half hexagon

Based on these estimated values, the overall manufacturing cost of the MMTF adds up to about 31.800 EUR. At this point it has to be kept in mind that this estimation contains no discount and is considering prototypical manufacturing according to the presented manufacturing chain. As it can be seen, the finishing part which is required due to heavy thermal deformations during welding is dominating the manufacturing cost. This may be avoided by substitution of the welding and annealing part with casted structures when it comes to mass production. This result confirms the results of the ecological analysis. As raw steel keeps obligatory, further research should be carried out in assessing the performance of casting or different joining techniques.

3. Wireless Sensor Nodes (WSN)

For the implementation of the required sensing and identification skills beyond the initial mechanical properties of the frame, microsystem technology by means of wireless sensor nodes is introduced to the MMTF. A minimum set of ten units is attached to the setup considered in section 1.2. Each unit includes sensors, data processing, wireless communication and power supply. The achievable degree of miniaturization as well as cost effects of large scale production allow for a high spatial distribution of the sensing task even at locations that can hardly be reached by conventional, cabled electronic measurement equipment. In order to achieve reasonable operating times without the need to exchange batteries apart from planned maintenance intervals, functions effecting power consumption were adapted specifically to the chosen use case of the MMTF. However, to account for future needs to extend system requirements without the need for a complete redesign of the node, a modularized design approach was applied to WSN in conjunction to the general concept of the MMTF. This includes standardized interfaces for additional sensors as well as options for autonomous power supply.

The currently available prototype of the WSN has a size of 20 mm x 65 mm and is shown in Fig. 5. It includes peripheral components and substrate material, e.g. an USB interface, for testing and programming purposes that will not be included on the final board and is therefore neglected in the following analysis.

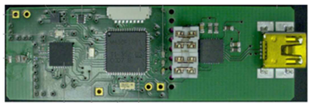

Fig. 5. Current prototype of wireless sensor node for functional evaluation

3.1. Intended assumptions for the production of WSN

To carry out the LCSA for the printed circuit board, assumptions have been made and system boundaries have been defined, comparable to the assessment of the MMTF. Generic data sets using ‘GaBi6 Extension database XI: Electronics’ were used to assess the demonstrator. Due to the complexity and variety of microelectronic components available on the market, generic databases can only represent a limited set of potentially suitable component data sets. This circumstance requires the user to fully understand the packaging type and implemented technology of both, generic data set and actual component investigated to come up with an assumption that relates the component under investigation to a reference data set and adequate scaling factor.

Tab. 2 includes the list of components assessed for the sensor node, comprising active and passive components as well as the printed circuit board (PCB) and solder paste utilized during assembly. Whenever available, data sets corresponding to the exact package and technology were selected, e.g. in case of the multilayer ceramic capacitor (MLCC) in standardized SMD (surface mount device)) size 0201 or the 4-layer PCB board made from FR4. For some parts scaling was then done based on weight for the reference data set closely matching count of terminals and overall size.

Tab. 2 Components included in one unit of a WSN

	Component	Package	Terminals	Qt.
Active components	µController	VQFN	64	1 p.
	Transistor	BGA	4	1 p.
	RF transceiver	VQFN	28	1 p.
	LED	SMD, 0201	2	3 p.
	Voltage converter	SON	10	1 p.
	Realtime clock	LCC	8	1 p.
	Temp. sensor	SOT-563	6	1 p.
	Acceleration sensor	LGA	12	1 p.
	Oscillator 32 MHz	SMD	4	1 p.
	Oscillator 32 kHz	SMD	4	1 p.
Passive components	Capacitors	SMD, 0201	2	13 p.
	Inductors	SMD, 0201	2	3 p.
	Resistors	SMD, 0201	2	8 p.
Assembly	PCB	n.a.	n.a.	1240 mm²
	Solder paste	n.a.	n.a.	80 mg

For selected packages, samples were prepared for cross-section polish and x-ray to determine the actual size of the silicon chip inside the package. Along with data sheets on material composition and descriptions of the specific packaging technologies involved, this additional information was used to determine the best suitable match for the active devices. However, since all generic data sets represent a fair average of the percentage material composition available on the market, there is still a degree of uncertainty left in the results.

3.2. Carbon footprint of WSN

The considered data sets claim to cover the life cycle from cradle-to-gate with each component providing a single process of in- and output streams that can be aggregated to an overall result for the sensor node. Assembly of the components is considered by an additional SMD assembly process that is directly linked to the chosen substrate material and size. Therefore, environmental impacts can be traced back to component level and the related assembly only which is sufficient in this stage of the assessment. The carbon footprint results describing the environmental dimension of the sustainable footprint are presented in Fig. 6.

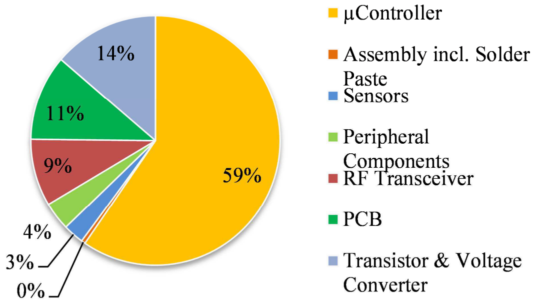

Fig. 6. Sources of CO2-eq. in wireless sensor units (Total: 1.975 kg CO2-eq.)

3.3. Manufacturing costs of WSN

For the assesment of LCC within the sustainable footprint of the Tiered approach, direct production costs of the sensor nodes were approximated based on the pricing for a quantity of 1000 pieces per component. Although, pricing for the test boards used for the limit number of demonstrators was comparatively high, a customary price for the PCB and the related assembley process was assumed. It has been shown, that the active compenents along with the required precision oscillators for synchronisation account for about half of the costs of one complete sensor node. The current price of 28 EUR per unit does so far not include the battery and can further be reduced as soon as higher production volumes will be achieved.

A detailed cost overview can be found in Fig. 7. Costs directly related to the production of the presented sensor node itself range from 10 EUR up to 50 EUR per sensor depending on the total production volume and chosen technology. Batteries would increase costs by at least 8 EUR per 3 year cycle, not including costs for service, e.g. installation and battery replacement.

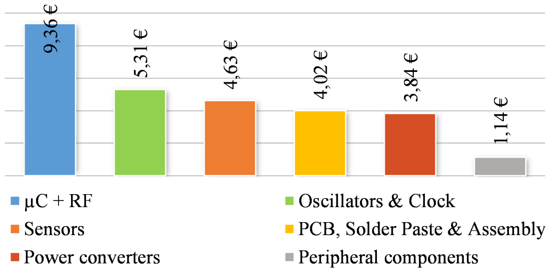

Fig. 7. Cost per unit per component category

3.4. Fair wage assessment of WSN

Unlikely the MMTF, the WSN consists of more components. Furthermore, the components have divers origins. Nine different countries has been involved in the production of the sensor nodes – Germany, USA, Japan, Thailand, China, Taiwan, South Korea, Malta and Phillipines. Fair wage impacts are heavily depending on the country and sector conditions.

Therefore, within the Fair wage assessment, it was focused on different worker types taking into account the various production locations. Non-poverty wages, minimum wages and living wages has been considered on a country and sector level. According to [24], [25] and [26] the highest risks has been located for Thailand, Philippines and Taiwan. The detailed results can be taken from Tab. 3.

Even though the tracking of the concrete origin for electronic components seems even more challenging then for the production of the MMTF, it is decisive. Only if the far upstream end of the supply chain appears transparently worker salary can be determined and influenced sustainably. As soon as the step from piece to mass production is performed, tracking of especially the identified hotspot countries with very high need to be performed.

Tab. 3. Evaluation of the risks of wage below poverty line according to the involved trades

Process	Relevant countries	Trade	Risk
Active components	USA	IT hardware engineer	very low
	Japan	Average IT worker	very low
	South Korea	Average IT worker	very low
	Thailand	Average IT worker	very high
		IT hardware engineer	medium
	China	Average IT worker	medium
		Average IT technician	low
		Average IT engineer	low
	Philippines	Average IT worker	very high
		Average IT technician	very high
		Average IT engineer	very high
	Malta	Average electrical & electronics worker	very low
	Taiwan	IT junior level worker	very high
		Average engineer	low
Passive components	Japan	Average IT worker	very low
Other components	Germany	IT electronic technician	very low
		System engineer	very low

4. Sustainability hotspots and results

A sustainable footprint has been adapted for both the MMTF and the WSN to describe the sustainable performance of the developed flexible manufacturing systems. This is done by performing a Carbon footprint analysis, a Fair wage assessment and an evaluation of the Manufacturing costs.

Whereas, the Carbon footprint is clearly dominated by the production of the MMTF more thorough by the raw material production, hotspots in the Fair wage assessment have been found more crucial for the electronic components used for the production of the sensor nodes. The overall manufacturing costs are dominated by the MMTF. For a reasonable use in the context of sustainable value creation, one has now to improve the specific insufficiencies found in the analysis. Therefore, the previously announced advancements will be followed. In addition, a broader picture in terms of sustainability performance is targeted as a logical next step. Further impacts have to be included to broaden the validity of the environmental, social and economic results.

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