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An evaluation of building sets designed for modular machine tool structures to support sustainable manufacturing

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Abstract

The modularization of machine tool frames is an approach when designing new machine tool structures in a sustainable context. By integration of microsystem technology and designing lightweight modules, a smart alternative to conventional machine tool frames is developed. In previous studies, this concept has been evaluated along with a compilation of the possible use-case scenarios and the potential benefits from using modular electronics. In the presented paper, the geometric requirements from the selected use-case scenarios for machine tool structures are identified by dividing the structures in their ideal mechanic equivalents. A set of rules is developed driven by the generalized geometric requirements of the machine tool frames. Three different approaches of polyhedral building sets are shown and evaluated for their merits based on criteria of geometric functionality and sustainability. Finally, a prototypical modular portal frame is presented for the proof of concept.

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Keywords: Sustainability; Machine Tool; Modularity; Scalability; Building Set;

1. Introduction

The design of new machine tools is traditionally driven by attributes like productivity, accuracy and reliability. But since the early 1970s, the public awareness of the limited nature of resources began to increase [1]. Hence, beside economic criteria, the necessity for sustainable designs becomes more and more evident. The global market situation nowadays is mainly characterized by short development cycles and a wide range of different product configurations. This trend is contrary to the long average lifetime of machine tools. According to [2], 80% of machine tools are retrofitted after 5 to 10 years and the average life span is more than 25 years. Furthermore, product specifications usually change numerous times so that there is a strong need for fast responsiveness to new production chains.

Along with the increased power of computer numeric controls, those requirements led to the development of so called Reconfigurable Manufacturing Systems (RMS). They consist of modularized system components (e.g. spindle, linear guide or tailstock) and combine more than one manufacturing process in a single machine tool.

Various other examples of modular designs have been seen in manufacturing systems like machining center, transfer lines and flexible manufacturing systems. The developing history of modular design can be found in [3].

Preliminary work in modular design of machine tool frames was done by KOENIGSBERGER by proposing cellular structures made of volumetric primitives [4]. This idea was based on the work of HERRMAN and BRANKAMP which defined the term Building Block System (BBS) [5].In the early 1960s, DOI proposed the four principles of modular design [6]. ITO did further investigations and pointed out, that the principles of separation and unification are for now difficult to address [3].

Although the modularization of the machine tool periphery has a long history and is a well-developed field, machine tool frames are still commonly casted monolithic structures or made of welded steel. In the presented approach, the principle of separation was implemented in the context of the machine tool frames to help determine the geometric requirements of the module to be designed. The principle of unification is inherent in the design of the modules, as the goal is to develop a single modular building set for machine tool frames. An

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evaluation of the connection between the modules was done within the geometric perspective of polyhedra and will be further considered in future development of the modules. The considered use-cases and further sustainability discussion can be found in [7].

PUTNIK ET AL. point out, that there are two basic principles of scalability, which are relevant for manufacturing systems [8]. The first principle describes the up- or downsizing of the product size. The second principle resembles to an increased or decreased production volume [9].

In the presented modular machine tool approach, the first principle of scalability was fulfilled by a fractal approach. The shapes themselves should be able to grow bigger by generating a scaled up version of their original shape. The second principle was fulfilled by taking universal interconnectivity into account, i.e. the interfaces of the modular building sets were designed to enable the connection of every module to every module. This satisfied the described requirements for modular machine tool frames.

2. Derivation of basic structures

The previous publication [7] describes the motivation for the development of lightweight and accuracy optimized (LEG^{2}O; German acronym for Leichtbau sowie gewichts- und genauigkeitsoptimierte modulare Werkzeugmaschinen-gestelle) modules which can be used to construct modular machine tool frames. By evaluating the most common machine tool types with regard to the modular machine tool frame approach, feasible use-cases could be identified. The design of such a modular building set used to construct machine tool frames requires further analysis of the present machine tool structures. The scope of this section is to derive the geometric requirements from prior research on structural configurations of machine tool frames. The top layer of Figure 1 shows the selected machine tools which are identified as use-cases for the implementation of the modular LEG^{2}O approach.

An extensive library of structural configurations is published in machine tool handbooks and research topics related to modular design of machine tools. Weck et al. and Brecher et al. classify turning machines with respect to the types of bed and relative motion between the tool and the workpiece. Both studies describe various configurations for horizontal and vertical boring machine combined with a milling process [[10], [11]]. CHEN synthesizes all possible structural configurations of three-, four- and five-axis machining centres [12]. HIRSCH ET AL. classify the machine tool frames as open or closed form structures based on the force flow and show four generic forms of machine tool structures viz. bed frame, angular frame, C-frame and portal frame [13].

Figure 1 summarizes the existing structural configurations of the selected conventional machine tools from the available literature. The arrows indicate which frames are used for the specific machine tool types. As it can be seen, portal frames, C-frames and bed-type frames are used commonly. The structural configurations of these selected machine tools can be represented as the following generic forms:

- Orthogonal bed frame
- Inclined bed frame
- Portal frame
- C-frame
- L-frame

By analysing these frames, similarities can be found. Hence, they can be further disintegrated into components which fulfil particular geometric requirements of the complete machine tool frame. The combination of allowed degrees of freedom between the components of these frames enables further flexibility in the functioning of the different machine tools. These structural components were identified as a column, a beam, a Cartesian bed i.e. structures expanded in Cartesian coordinates and an inclined bed. The geometrical characteristics of the structural components have been compiled in Table 1. For completeness, columns and beams are shown separated as vertically and horizontally growing

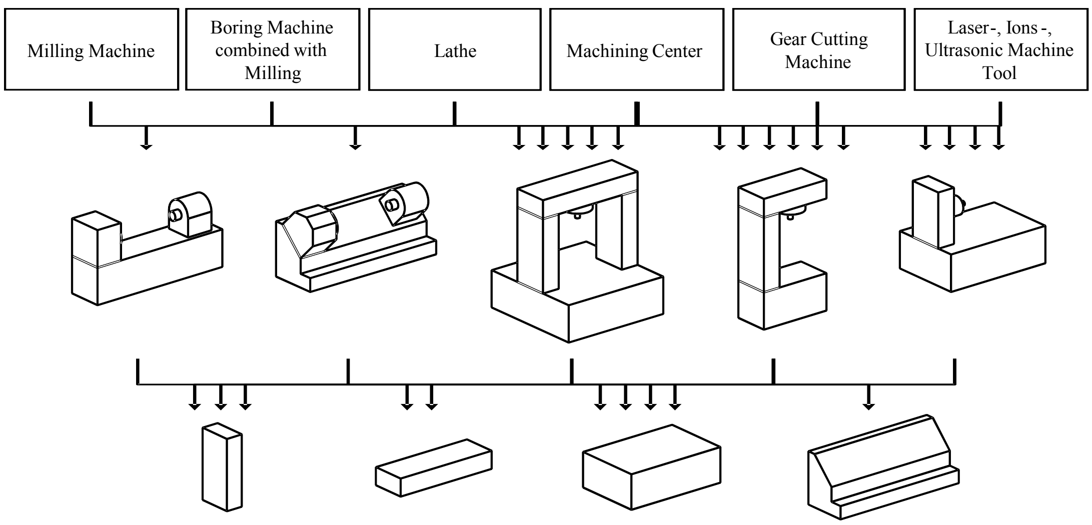
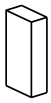
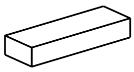
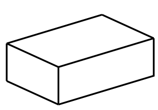
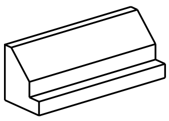


Figure 1. Use cases for modular machine tool structures and derived basic forms.

components, although they have similar geometric structures. Beam and bed components were distinguished by defining the aspect ratio, i.e. the division of the longest side divided by the shortest side. Hence, the machine tool bed can be described as a planar growing component with low aspect ratio and beam like structures inherit high aspect ratios.

Table 1. Compilation of basic structures.

Component	Geometric characteristic
 Column	• Vertically growing component • High aspect ratio
 Beam	• Horizontally growing component • High aspect ratio
 Bed	• Planar growing component • Low aspect ratio
 Inclined Bed	• Planar growing component • Low aspect ratio • Angular functional surface

3. Library of primitives

In the previous section, structural shapes and geometries were identified which are necessary to build the proposed machine tool frames. The identified basic machine tool frame elements were broken down into their volumetric shapes and are available for further analysis. The next step was to find a suitable library of modular building structures which fill up the required volumes and satisfy certain criteria. Therefore, a set of rules were described to reduce the wide solution space and allow for the selection of libraries of building modules. The following section summarizes the four rules.

3.1. Rules for polygon building set

i. As formerly described, the modular building set has to fulfil the two principles of scalability. A fractal approach is chosen, i.e. by assembling a specific number of single modules of the library the same shape in a bigger scale is recreated. Therefore, the first principle is taken into account without exceeding the size of the original building elements. This also limits the weight of the modules which especially is advantageous considering the mobility and manual operability of the single elements.

ii. Universal interfaces are an approach to fulfil the second principle of scalability. Speaking in terms of geometric volumes, the polygon shape should be equilateral. To limit the overall complexity of the system, the evaluated elements will also be equiangular. This reduces the set of possible shapes to the class of regular polygons. In other words, somehow distorted shapes are not taken into account at this point.

iii. The mechanical suitability of the developed modules for the use-case as a modular machine tool frame cannot be evaluated in this early stage because of the wide possible solution space. Hence, feasibility and minimized compliance are proposed by reducing the set of possible polygonal shapes to tilable polygons. Those polygons offer gap-free connections which guarantee full planar contact within the building set. Inserting rule ii, this results in the three so called regular tilings (Platonic tilings) [14] viz. triangles, squares and hexagons.

iv. Due to the application as a modular machine tool frame, special conditions for the possible directions of the planes have to be met. Derived from the structures shown in Figure 2, there is a high demand for rectangularity. Nevertheless, inclined planes are also widely used in machine tool structures. Angular grow directions offer the needed variety of design options to allow for more flexible structural shapes and therefore contribute to better force flows and overall performance of the machine tool structure. Hence, the building set has to support different plane angles of a certain variety and 3 axes Cartesian grow at the same time.

A summarization of the rules is given in the Table 2.

Table 2. Rules for shapes of modular machine tool frames.

Rule Nr.	Description
i	Scalability, so that the outer edges form the same shape as the original building block
ii	Regular polygon for universal connections and reduced system complexity
iii	Gap-free connection for increased mechanical stiffness
iv	Support for Cartesian grow and angular planes

3.2. Analysis of building sets

As described in rule iii, at this point the possible module shapes are limited to triangles, squares and hexagons. The next step is to extend the 2D planar polygons into 3D space and form volumetric structures.

To satisfy the need for rectangularity described in rule iv, all basic modules will be an extrusion of the geometric primitives described by rule ii. Therefore, every module has implicit at least two rectangular faces. The linear extrusion also works well with the demand of gap-free connections of rule iii. The three basic prismatic volumes and their assemblies are shown in Figure 2. It is also shown, that all of them fulfil the rule i. Nevertheless, the required Cartesian and angular grow directions cannot be realized with a pure cubic or hexagonal building set without using zigzag building patterns. To solve this problem, the two approaches have to be extended to a building set of at least one more block per set.

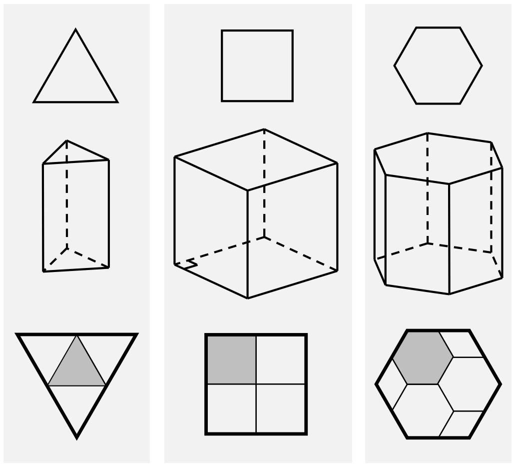


Figure 2. Tileable basic regular polygons (top), extrusion to prisms (middle) and upscaling of the elements (bottom).

3.3. Extension of building set

As pointed out in the previous part, the cubic set cannot offer an angular plane. The possible growing directions are strictly on a Cartesian grid. On the other hand, the hexagon or triangle prisms are not able to grow in a full Cartesian coordinate system. Just when allowing a zigzag building approach, three perpendicular directions in average become possible.

To overcome with these problems, all approaches have to be extended to a building set of more than just one primitive element. When the square is diagonal cut in half, an isosceles triangle is generated which solves the problem of angularity. By using the triangle beside a square, a 45 degree growing direction is introduced to the building set so that rule iv becomes fulfilled. By using just one isosceles prism, system complexity is kept low, but on the other hand only one additional angle becomes possible.

The hexagon approach itself can be extended by cutting the hexagonal prism along two opposite corners into two equal halves. This allows the set to grow in Cartesian directions and offers angular planes of 60 degree. As it is the same in the square set, only one angular plane can be generated.

Similar to the other polygons, the triangular prism can be cut from one corner into two triangles of the same area. This offers another advantage beside the avoidance of zigzag patterns. It gives an additional new face normal to further extend the structure.

Figure 3 gives an illustration of the described issue and shows the complete three approaches for a modular building set for machine tool frames. The highlighted, non-regular shapes are the suggested extensions to satisfy all rules without the need of building zigzag patterns.

In the next section, a thorough comparison and an evaluation is made for deciding on the optimal building set for the given machine tool structures.

4. Evaluation of building sets

The set of polyhedra which were proposed in the previous section were used to construct the basic components derived from studying the frames of the use-case machine tools. The three proposed polyhedral sets are:

- Triangular set
- Square set
- Hexagonal set

4.1. Geometric functionality and material consumption

The basic components of the machine tool frames viz. column, beam and bed were constructed using the proposed modular blocks as shown in Figure 4.

The blocks were stacked on top of each other to form a high aspect ratio structure which satisfied the requirements of a column component. The size of the cross section of such a column can be constructed as required since the patterns can be scaled up in the modular steps of the blocks (rule i). Similarly, the blocks were used to grow in a planar direction by connecting the rectangular faces from extrusion to form a high aspect ratio beam component or a low aspect ratio bed component. Due to the growth directions at 30 degrees and 60 degrees for the triangle and hexagon respectively, the growth step represented in the Cartesian axes for these blocks is the projection of these angles on the axes which is described further in this section.

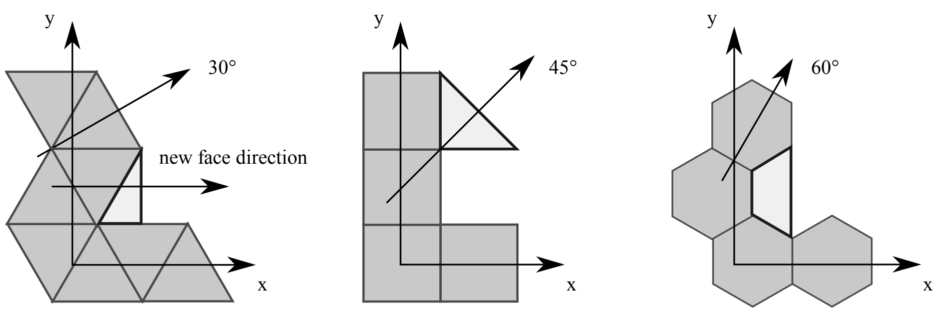


Figure 3. Triangle building set (left), square building set (middle) and hexagon building set (right).

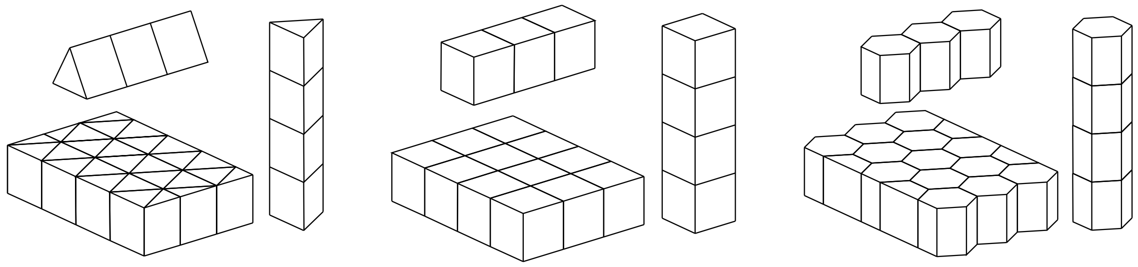


Figure 4. Frame components filled with the proposed building sets: Triangular set (left), square set (middle) and hexagonal set (right).

The proposed module shapes were evaluated based on their geometric properties and tiling patterns to cover an area in planar orthogonal axes. The selected cross sections for the modular building sets are capable of forming gap free tiling; but the tiling patterns for each of the sets are different and these patterns create a growth length step in which the blocks can be propagated along a direction.

Table 3 Geometric analysis of building sets.

	Triangle	Square	Hexagon
Side length for equal circumference (a)	$^{1}/_{3}$	$^{1}/_{4}$	$^{1}/_{6}$
Growth step in X direction	$^{a}/_{2}$	a	$^{3a}/_{2}$
Growth step in Y direction	$^{\sqrt{3}a}/_{2}$	a	$\sqrt{3}a$
Blocks per unit length			
In X-direction	$\lceil ^{2}/_{a} \rceil = 6$	$\lceil ^{1}/_{a} \rceil = 4$	$\lceil ^{2}/_{3a} \rceil = 4$
In Y-direction	$\left\lceil ^{2}/_{\sqrt{3}a} \right\rceil = 4$	$\lceil ^{1}/_{a} \rceil = 4$	$\left\lceil ^{1}/_{\sqrt{3}a} \right\rceil = 4$
Area covered	$^{\sqrt{3}a^2}/_{4} = 0.048$	$a^2 = 0.0625$	$^{3\sqrt{3}a^2}/_{2} = 0.072$

To compare the different building sets, the sizes of the elements have to be normalized. This was done by unifying the material consumption for the production of the building sets. As the volumetric structure of every model is an extrusion of the polygonal shape, normalization can be achieved by considering an equal element circumference of 1 in all three building sets. This is shown for the three different cross-sections and the respective edge lengths of the polygons in Table 3.

The orientations of the polygons are shown in the Figure 5. The steps in which the polygons can be tiled along the shown orthogonal directions was calculated based on the edge lengths and the geometry of the tiling patterns. The square has an equal modular step in Cartesian axes when it is used to grow a structure. This step is equal to its edge length. The triangular and hexagonal prisms have non-orthogonal side faces which results in an angular growth of the structure.

The upper integer modulus of the inverse growth step in a direction represents the number of blocks required to completely cover a unit length. As it can be seen in Table 3, the value of required blocks per unit length is same for the square and the hexagon, but more for the triangle in X-direction. Further, the area covered by each of the polygons was calculated and it was seen that the area and thus the volume covered by the hexagon was maximum among the proposed polygons. Speaking in other words, the hexagon is the lightest and most material saving approach for filling structural volumes.

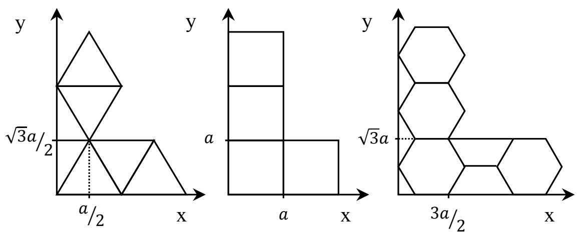


Figure 5. Tiling growth of building set in Cartesian axes.

At this early design stage, another criterion could be derived to give an estimation of the manufacturing effort and thus an indicator for the costs for build the modular machine tool frame. This was done by a connection analysis in the next section.

4.2. Connection analysis

As gap-free connection is the chosen approach for stiff constructions and connections, the modular structures become very compact. Because of the modular nature of the building sets, error propagation occurs, i.e. the tolerances of every module add up which complicates the successful assembly of closed patterns. Hence, high accuracy manufacturing is needed to be able to assemble the different configurations. By analyzing Figure 3, one can obtain the connecting faces when assembling the single modules to bigger structures.

Along the extrusion axes, the amount of connecting faces is always one. When building compact bed structures, the triangle has six connecting faces on one vertex. Different from that, the hexagonal set has three and the cubic set has four connecting faces on one vertex. This can be seen as an indicator for the manufacturing requirements and the overall accuracy of the modular assembly.

Moreover, the connectivity of the modules can be assessed based on the neighboring connectivity of the modules. The triangular and square tiles share an edge with three and four adjacent modules respectively. The hexagonal module shares a rectangular face with its neighboring modules which is analogous to the 2D tiling analysis published in [15]. It is safe to assume that connection mechanism can only be implemented on a surface instead of an edge. This implies a positive connection with all adjacent modules in the hexagonal grid. Consequently, the planar tiling of the hexagonal modules can be predicted to be stiffer compared to the triangular and square modules.

Hence, the evaluation of geometric functionality and connectivity of the building sets suggest that the hexagon building set as a stiff and material saving thus economic and ecologic approach for modular machine tool frames.

5. Gantry portal frame as use-case

A gantry portal frame is presented in Figure 6 as a use-case example which is modelled using the proposed hexagonal building set without further analysis. The hexagonal prism used is of 200 mm inscribed diameter and extruded height. Due to its gantry-type, the working volume available is 1000 mm × 600 mm × 400 mm. The transverse beam shown in the model can translate along the two column rails.

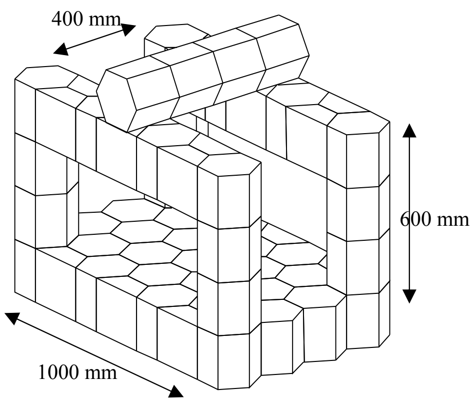


Figure 6. Gantry portal frame modelled using hexagonal building set.

6. Conclusion

In this paper, generic forms were derived from the use-cases of modular machine tool structures proposed in [7]. A set of rules for modular machine tool frames are given and applied to the LEG²O concept. Derived from these rules, polygonal shapes were presented which give the basic form of the building elements. The forms are triangles, squares and hexagons. They were converted into volumetric structures by linear extrusion.

By evaluating the geometric characteristics and the interconnection of the single elements, a trend was derived. The hexagonal set on one hand offers the highest ratio of used material to covered volume. Therefore, it promises to be a material saving approach to replace conventional machine tool frames. On the other hand, the hexagon has the least amount of connecting faces which simplifies the assembly and lowers the overall manufacturing effort. Due to the modules size, single elements can easily be exchanged by humans allowing for repair and high reusability.

These aspects, addressing the economic and ecologic dimension of sustainability [16], have now to be further investigated based on LCA and LCSA on more detailed product instantiations. Due to its geometric flexibility, established concepts of machine tool periphery can easily be integrated. Nevertheless, the sustainability of peripherals is still an open research question which has to be answered in the future.

In summarization, the hexagonal building set was found as the most promising design for a sustainable replacement of conventional frames with modular machine tool frames.

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