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Principles for Interconnection of Modular Machine Tool Frames

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Abstract

An approach for reusable and adaptable machine tool frames is the modularization of the frame structure by breakdown to hexagonal primitives. The design of small light weight modules allows for the assembly of a high variation of different geometries and enables scalable structures. However, a core issue in designing modular products is the proper definition of interfaces within the own product family and the outside, by which the usability and flexibility of the modular structure is mainly influenced. In the context of modular machine tool frames, conventional mechanical criteria like stiffness, reliability and cost are key factors when designing new joining techniques. Taking sustainability into account, additional aspects of social, economic and ecologic dimension become important. This paper presents a study on reusable connection principles for modular machine tool frames and gives an evaluation according to sustainability criteria by using a fuzzy analytical network process.

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1. Introduction

The principle of modular and reconfigurable machine tools (RMT) is proposed to be a necessary step towards meeting modern markets requirements of rapidly changing product and manufacturing specifications. It has therefore been formulated as one of the great challenges of future manufacturing [1]. By adapting the machine tools to manufacturing demands, economical benefits are foreseen [2]. In case of modular RMT, the equipment can be treated as a resource, in which efficient use and reuse result in ecological benefits. Hence, RMT promise a sustainable sound solution for future manufacturing scenarios.

As ITO [3] pointed out in his book on modular design for machine tools, detailed research has to be carried out in the fields of interconnection and connection interfaces especially when designing reconfigurable and modular machine tools. KIENZLE [4] is reported to be the initiator of this research topic and since then, research aimed at scientific understanding of the structural behavior of coupling points and machine tool joints. Despite the different design of machine tool joints, there exist two certain key characteristics:

- Every coupling point results in decreased static stiffness in direct comparison to rigid solid connections [5]
- Nonlinear effects like micro friction increase damping properties in every coupling point of the mated parts [6]

A classification of different machine tool joints can be found in literature [3]. Hereby, sliding joints, stationary and semi stationary joints are differentiated. The scope of this paper is the analysis of connection principles for structural modules of a modular machine tool frame. Hence, no macroscopic relative movement occurs between the modules and thus only stationary joints are considered.

In this paper, the authors start by describing the joining task and summarize key requirements to reduce the solution space of possible alternatives. A morphological box is subsequently developed to characterize connection principles and eventually used to derive alternatives for the evaluation using a Fuzzy Analytical Network Approach (FANP).

The Analytic Network Process (ANP) is a generalization of the Analytical Hierarchy Process (AHP) developed by SAATY [7, 8] in the 1980s. It is a widely used methodology for

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decision makers (DM) to choose optimal alternatives concerning clusters and nodes of criteria and properties.

The basic idea is to build up a network of clusters and nodes and define their connectivity. By pairwise comparison of all elements with respect to other elements, principal dependencies are found and compiled into a supermatrix. In the following step, the supermatrix becomes weighted by multiplying the cluster entries with chosen priorities. In the last step, the limit of the weighted supermatrix is calculated by raising it to high powers. Within the limit supermatrix, the optimal solution can be obtained by comparing raw priorities.

In preliminary work, the ANP was successfully used to evaluate discrete fasteners, integral attachments, adhesive bonding, energy bonding and other connections with respect to design for disassembly (DFD) [9].The considered clusters were assembly concerns, in-use period concerns and disassembly concerns. In this study, the idea will be transferred onto a concrete design problem and extended by taking the three sustainability dimensions and manufacturing concerns into account.

In a predesign phase without detailed sustainability assessment, quantified scores are difficult to assess. In addition to that, absolute sustainability targets are still topic of extensive research. Therefore, an FANP is preferred over an ANP when evaluating sustainability indicators. One way to deal with those uncertainties is to base the pairwise comparison on a blurred grading, e.g. use fuzzy triangular numbers (FTN) for pairwise comparisons. A detailed description of the FANP can be found in literature [10]. The evaluation in this study is done via a MATLAB program based on FANP theory [11].

2. Preliminary study

In preliminary work, a hexagonal building set is proposed as the most resource efficient and flexible solution for geometric adaptation of machine tool structures [12]. This novel approach enhances flexibility and modularity of RMT by the modularization of machine tool frames. The inevitable decreased stiffness of joined modules is coped with the integration of active modules and wireless and autarkic sensor systems. This micro technology enhanced system architecture can be seen as an extension of preliminary work on building block systems (BBS) done by KÖNIGSBERGER ET AL. [13] in the early 1960s.

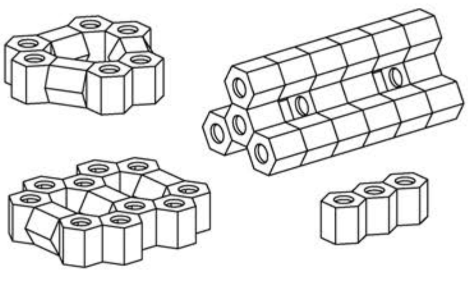

Fig. 1. Hexagonal approach for flexible and scalable machine tool frames with exemplarily frame topologies.

The use case of the proposed building set as a way to assemble modular machine tool frames imposes requirements on the connectivity of the single modules. In preliminary work, a structural building set was identified as suitable for generating versatile machine tool frame topologies which is illustrated in Fig. 1 [12].

2.1. Definition of the joining task

Fig. 2 gives an overview on the different arrangements derived from Fig. 1. The grey arrows indicate possible ways to access the inside faces of mating parts. By adding building blocks incrementally, the shown structures can be assembled using the three different configurations A-A to C-C. As it can be seen, the joining task consists of mating faces in various ways. For the evaluation of different principles, criteria and their proper weighting have to be defined.

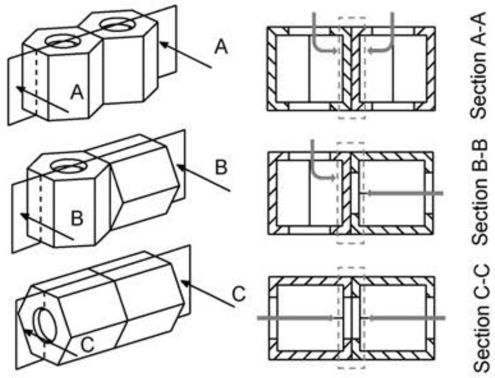

Fig. 2. Different arrangements of hexagonal building blocks; access to coupling point is indicated by grey arrows.

One key issue is the accessibility of the coupling points in modular systems. The hexagonal building block is designed with one hole at the top and one at the bottom face. The holes can be used to access the inside of the blocks outer faces. However, additional holes should be avoided though they decrease the stiffness of the modules. Different joining techniques may require the accessibility of both faces of a coupling point at the same time, e.g a nut and a bolt vs. a bolt and a thread. Although accessibility seems to be granted at all times, angling of 90° occurs in some cases. Additionally, the holes might be covered by previously assembled blocks and therefore are unavailable for assembling additional modules.

2.2. Reduction of solution space

In order to reduce the solution space of possible connectivity principles, eliminatory criteria are formulated which directly influence the dimensions of sustainability in a positive way. The following table gives an overview on the findings. The Table 1 describes the findings for general criteria directly or indirectly affecting one or more sustainability dimensions and therefore will work as eliminatory criteria for joining principles.