ANALYSIS METHODOLOGY AND ASSEMBLY RULES FOR THE RAPID AND FLEXIBLE DESIGN OF COMPOSITE SYSTEMS

D.M. Emiris[1], D.E. Koulouriotis[2] and N.G. Bilalis[3]

[1]*Department of Production Management and Technology*
University of Piraeus
e-mail: emiris@unipi.gr

[2]*Department of Production Management and Engineering*
Democritus University of Thrace
e-mail: jimk@pme.duth.gr

[3]*Department of Production Engineering and Management*
Technical University of Crete
e-mail:bilalis@dpem.tuc.gr

Abstract

In order to meet diverse customer requirements and to maintain manufacturing competitiveness, next generation manufacturing systems must exhibit such features as rapid development and deployment, flexibility with respect to product quantity and variety, and reusability of equipment. The Holonic Manufacturing Systems (HMS) represent one of the most recent approaches in this context. An HMS makes innovative use of technical advances in computers, software, sensors and distributed autonomous systems technology to realize the required features of next generation manufacturing systems and can be regarded as a complementary technology to CIM. The holonic assembly approach is utilized in this article as a basis for the development of a composite construction and a paradigm to show the major steps in the implementation of a large variety of similar systems. An actual prototype was constructed using LEGO blocks; this system is composed of specific subsystems/ subassemblies, which were developed by using both electrical and pneumatic motors, interconnected in a manner that permits the motion of more than one subsystem with a single motor's motion. The combined structure is able to handle the assembly of different products; at the same time, the construction process results to the accumulation of significant expertise in the development and knowledge of the functionalities and properties of each subsystem, thus enabling their efficient use in other more complex structures.

Keywords

Flexible Assembly, Holonic Manufacturing Systems, LEGO.

1. INTRODUCTION

In order to meet diverse customer requirements and to maintain manufacturing competitiveness, next generation manufacturing systems must exhibit such features as rapid development and deployment, flexibility with respect to product quantity and variety, and reusability of equipment [2]. The *Holonic Manufacturing Systems* (HMS) represent one of the most recent approaches in this context. An HMS makes innovative use of technical advances in computers, software, sensors and distributed autonomous systems technology to realize the required features of next generation manufacturing systems and can be regarded as a complementary technology to CIM [3,4].

The term *holonic* arises from the word *holon* - a term originally coined by Arthur Koestler [5]. It is a combination between the Greek word "holos" meaning whole and the suffix "on", which suggests a particle or part. Holons are considered to be, at the same time, self-contained wholes to their subordinated parts *and* dependent parts when seen from the inverse direction. According to Koestler the sub-wholes/ holons are autonomous self-reliant units, which have a degree of independence and handle contingencies without asking higher authorities for instructions; at the same time, they are subject to control from (multiple) higher authorities. The first property ensures that holons are stable forms, which survive disturbances; the second property signifies that they are intermediate forms that provide the proper functionality for a bigger whole [8], called *holarchy*. A holarchy is a hierarchically organized structure of holons and a holon is a node of the holarchy. It is important to stress that: (i) each holon can receive and transmit signals; (ii) the behavior of the holons is more mechanized, stereotyped and predictable the further down in the holarchy they are; and (iii) a holon can be a part in multiple holarchies [1]. Whenever manufacturing elements are developed as holons, the desired manufacturing equipment and systems can be realized flexibly and rapidly by simple (and possible self-initiated) combinations or reconfigurations of elements.

In this article, the holonic assembly approach is utilized as a basis for the development of a composite construction and as a paradigm to show the major steps in the implementation of a large variety of similar systems. An actual prototype was constructed using LEGO blocks. The objective behind the use of LEGO blocks to implement the production system prototype was to assimilate real-world conditions in the construction of a system, through low-cost, easy-to-handle and flexible means, which provide sufficient insight in the development process parameters. It was intended in particular, to initiate the development process from the design phase, to take into account all the relevant factors that determine the final form of the system, to complete the construction and execute the operational controls, and to verify whether its operation conforms to the design specifications and the functional requirements set during the design phase. The following key targets - sufficiently generic in order to allow their application to any real construction- were set and all efforts focused in their fulfillment:

- *The system should be flexible*. The implemented system should not serve only one particular function, such as the production of a single product, but also to enable the production of a family of products with similar characteristics and at a satisfactory production rate. In case that this ability is not feasible without any changes in the form of the production line, then minor changes should suffice for the achievement of such flexibility; in other words, major improvement in flexibility should not require major changes in the production line.
- *The system should be expandable*. This is equivalent to saying that the system is evolutionary and is translated into the ability of interconnecting a system with other subsystems, systems or components, in order to create a more pluralistic (in terms of functionalities) production line.
- *The construction should be implemented in a short time and at a low cost*. This was achieved by capitalizing on the expertise in the creation of smaller, modular, functional components, which may be used or replicated as necessary. This leads to a formalization of the construction methodology, which results in an overall benefit in the development of modular systems.

The implementation of a system to satisfy these targets was feasible through the use of LEGO blocks, in order to construct a system under scale. The fact that one cannot draw conclusions for the mechanical behavior of the actual materials nor can one simulate operation in real environment with humidity and dust is considered a minus; however, they exhibit multiple advantages, such as:

- *The motion capabilities are extensive and practically unconstrained*. The use of the LEGO motors as motion generators, allow the achievement of translational and/or rotational motion.
- *The interconnection alternatives are practically unlimited*. LEGO blocks can be interconnected in many different ways, thus enabling the construction of any system, no matter how simple or complex it may be. The existence of several different types of pieces does not put any constraint in what will be constructed; in the contrary, one can build the same system in various ways and select the most appropriate one.
- *The system allows the operational simulation*. The repetitive, experimental operation of the construction, at any level during its implementation, enables the identification of problems that were not predicted during the design phase (such as the voltage drop in the motor ends), as well as the verification of conformance to requirements.
- *The system allows for the programming of the motor motions*. This is achieved by using the motion consoles, so as to have a realistic approach to the automatic operation of the system.

- *The cost of development is very small*. This is due to the fact that one can use the same pieces practically an infinite number of times, since they do not present any discernable difference in their mechanical abilities and behavior through their repetitive use. In addition to that, the cost of reengineering is minimized, which is definitely not the case in real constructions.

The constructed system is composed of specific subsystems/ subassemblies, which were developed by using both electrical and pneumatic motors, interconnected in a manner that permits the motion of more than one subsystem with a single motor's motion. The combined structure is able to handle the assembly of different products, as long as the union of certain parts is required; thus, the constructed system achieves the flexibility target. At the same time, the construction process evidently passes through the development of the distinct subsystems; this resulted to the accumulation of significant expertise in the construction and knowledge of the functionalities and properties of each subsystem, thus enabling their efficient use in other more complex structures.

The present article is structured as follows. In Section 2, the coding process of primitive LEGO components, as an essential step to construction of subsystems, is presented. The definition of possible interconnection methods and the steps towards the implementation of subsystems are given in Section 3. Section 4 summarizes the operation mode of the integral system and analyzes the fulfillment of the imposed targets. Finally, in Section 5, the benefits of the approach are enumerated and the future research paths are highlighted.

2. THE CODING PROCESS

The process of coding the distinct elements that will be used in the construction of any system is essential and must be carried out before the design of any system. The codes derived are self-explanatory, easy to use and facilitate the definition of interconnection possibilities. The elements were first categorized in the following 10 distinct groups:

- Bricks
- Plates
- Gears
- Axes
- Links
- Axes unions
- Belts
- Axes safeties
- Motion transmission
- Singular elements

Four-digit codes were used for the description of each element; in fact, this is the minimum number of digits that may be used for the accurate description of the elements. In this context, a digit may be any alphabetic (A-Z) or numeric (0-9) character (but not a symbol, e.g., &, @, etc.). A fifth digit may be appended optionally, to denote the color of the element; this may be desired for aesthetic reasons when random color alterations need to be avoided, however, the end-result in terms of operation and functionality is not affected by the color selection. The following table presents a delegation of these codes for some categories of building elements, shown in Figure 1. A full presentation of the codes is beyond the scope of this article. In certain cases, there exists a question mark instead of a specific digit; the question mark serves as a free agent that obtains numeric values only where by selecting a different number a new code is generated. In some codes, a digit may be redundant or self-explanatory; however, the digit is still present for uniformity reasons. Also, in certain codes, a fifth digit may denote the color of the element (Y for yellow, B for black, G for Grey).

Category	Description				Code
Brick	**B**rick	? (decades)	? (1-9)	With **H**oles	B??H
	Brick	**S**harp	? (1-9)	With **H**oles	BS?H
Plates	**P**late	? (width)	? (length)	**W**ithout Holes	P??W
Gears	**G**ear	**N**ormal	Of **S**ize	? (1-6)	GNS?
	Gear	With **I**ndependent	**M**otion	Of **T**eeth	GIMT
Axes	**A**xis	**N**ormal	Of **S**ize	?	ANS?
Axes unions	**U**nion	**P**arallel	**A**nd	**C**ollinear	UPAC
Axes safeties	**S**afety	For **N**ormal Axis	**S**hort	**W**ithout Teeth	SNSW
Motion Transmission	**M**otion	From **A**xis	To **B**elt	? (size 1-3)	MAB?
Singular elements	**S**ingular	For **C**onstruction	With **A**bility	Of **R**otation	SCAR

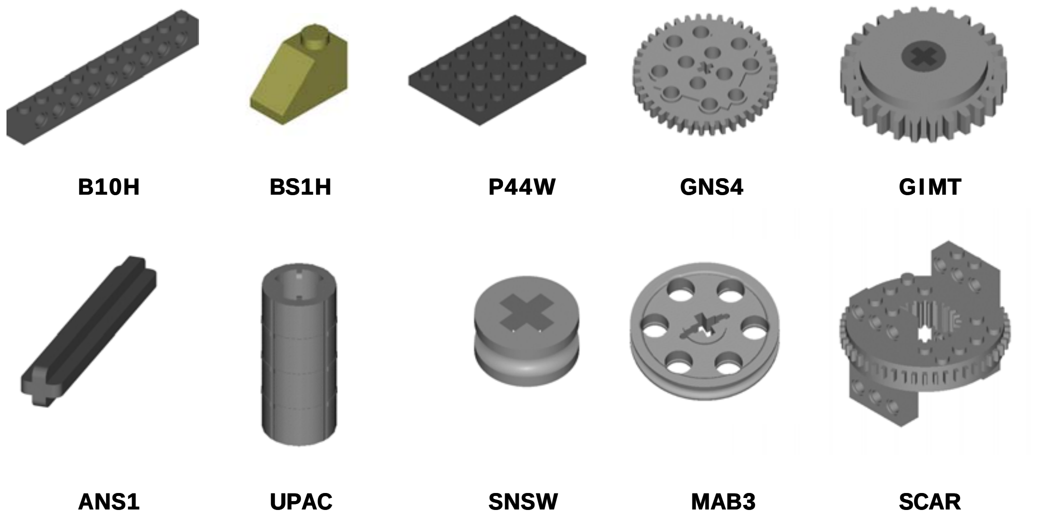

Figure 1: *Coding of Assembly Elements*.

A large number of available elements is used in the construction of the nine (9) subsystems below:

- The central part which is composed of the belt on which the process of the product takes place, the press that is moving on it and the motion mechanism for the press.
- Two small belts on top of which a press is placed along with their motion mechanisms. The press is used here to push the product from the central part.
- A special mechanism that is transmitting the motion from one motor to the motion mechanisms of the side belts.
- Two conveyor belts that bring the unprocessed product to the central part.
- A second special mechanism which utilizes the three pneumatic components and the air pump in order to place the unprocessed product from the conveyor belt to the central part at the desired position.
- Two rotational subsystems of the entire construction, which handle the output of the product.

Two of these subsystems are displayed in the Figure 2.

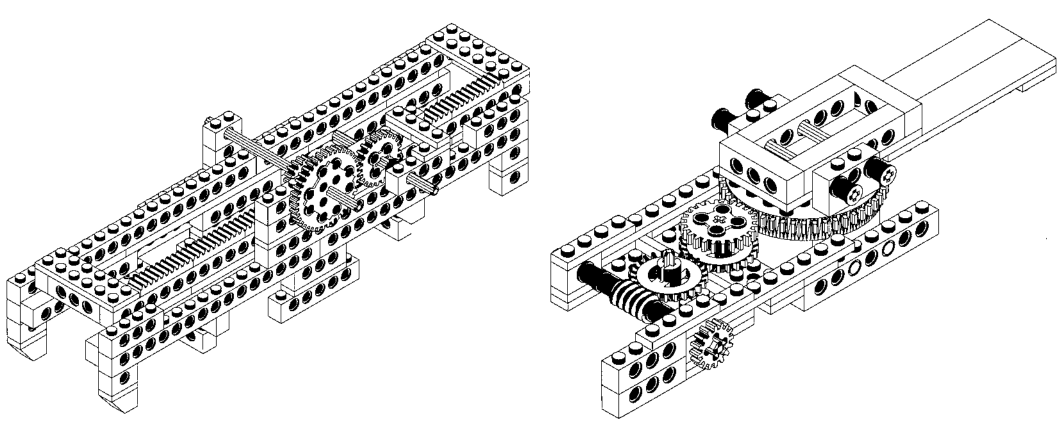

Figure 2: *The Small Belt Subsystem and the Rotational Subsystem*.

The motion of the mechanical parts of the assembly is performed by four motors. Two of these have low torque and high speed, whereas the other two have high torque and low speed. The two former ones are used for the motion of the presses, where the one moves only the central press and the other one moves the two side presses. The other two motors are used to move one conveyor belt and one rotational part. The entire system is displayed in Figure 3.

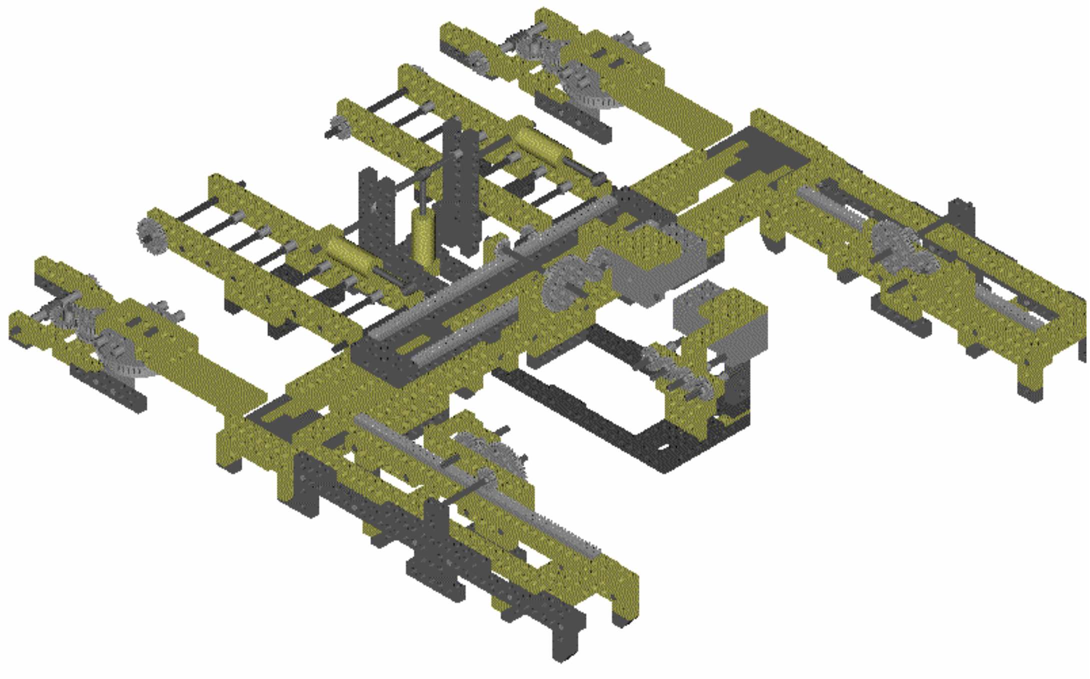

Figure 3: *The Complete Construction.*

3. THE INTERCONNECTION METHODOLOGY

The assembly of the composite structure may be performed by using one of two alternatives. The key parameters in the first approach are the orientation and the attributes of each element. The attributes of each element may be the holes on the side and the shapes in its top and bottom sides (Figure 4). Once these attributes are determined, a codified description for the interconnection is employed, which is similar to the assembly language in software development. Despite the fact that this approach is elaborate and accurate as it describes all the actions that lead to the interconnection, it results in very lengthy descriptions for a complex subsystem.

The second approach limits the needs to describe interconnections, since not all elements may be connected to all the others. The code used to describe a connection has a variable length and is used to determine the position of an element with respect to some other that is connected with. Connections that require a coded description concern, for example, these between a two bricks, or between two plates, or between a brick and an axis, etc. The explanation of each connection code is beyond the scope of this article; however, in order to illustrate this concept, the union of two bricks vertically in the third hole, is described as "**V**ertically in **H**ole **03** on the **L**eft side, **U**pwards" or **VH03LU** and is shown in Figure 4. Other connections do not require a coded description; the connection between two gears, for example, is unique and does not need further explanation.

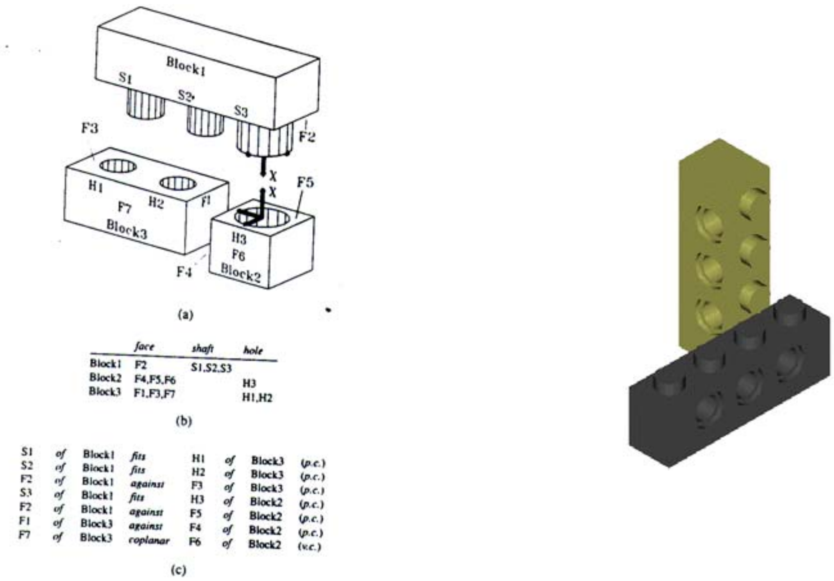

Figure 4: *The Alternatives of Codification of Assembly.*

In addition to the codification of the connections, the development of an assembly may be viewed as the union of holons so as to create holons at a higher level and finally a holarchy. The diagrammatic approach uses the symbols presented in the following table to denote the assembly process. The holarchy for the rotational subsystem is depicted in Figure 5.

Symbol	Explanation
	LEGO element.
	Composite LEGO element (e.g., base, chain, etc.), which cannot obtain a code. The properties of the element are shown inside the symbol.
	Non-plastic element, not relevant to LEGO. Its description is shown inside the symbol.
	Result from the union of certain elements without any further description.
	Result from the union of certain elements that will be used later in the same construction. It is described by a single letter.
	Final result of all the unions until that point.

4. ANALYSIS OF OPERATION

The main targets that was sought to accomplish were the flexibility and the expandability of the system as well as the reduction of the cost of development. As a first measure, it was attempted to minimize the number of different elements used and to use as many identical subsystems as possible, since in many cases, the cost of development is higher than the production cost itself. At the same time, many subsystems were employed in the development of distinct more complex systems and not in just one system – this is evidenced by the construction diagrams. As a result, instead of six subsystems, actually one has to produce only three and to replicate them. Once the subsystems were developed, they were assembled in a main construction. The operation of this construction was scheduled through careful identification of the activities involved and development of a distribution for the duration of each activity. The sequence of activities was modeled as an activity-on-node graph, whereas, the temporal display of the sequence of activities resulted through a Gantt chart, for each subsystem separately and the entire system as a whole.

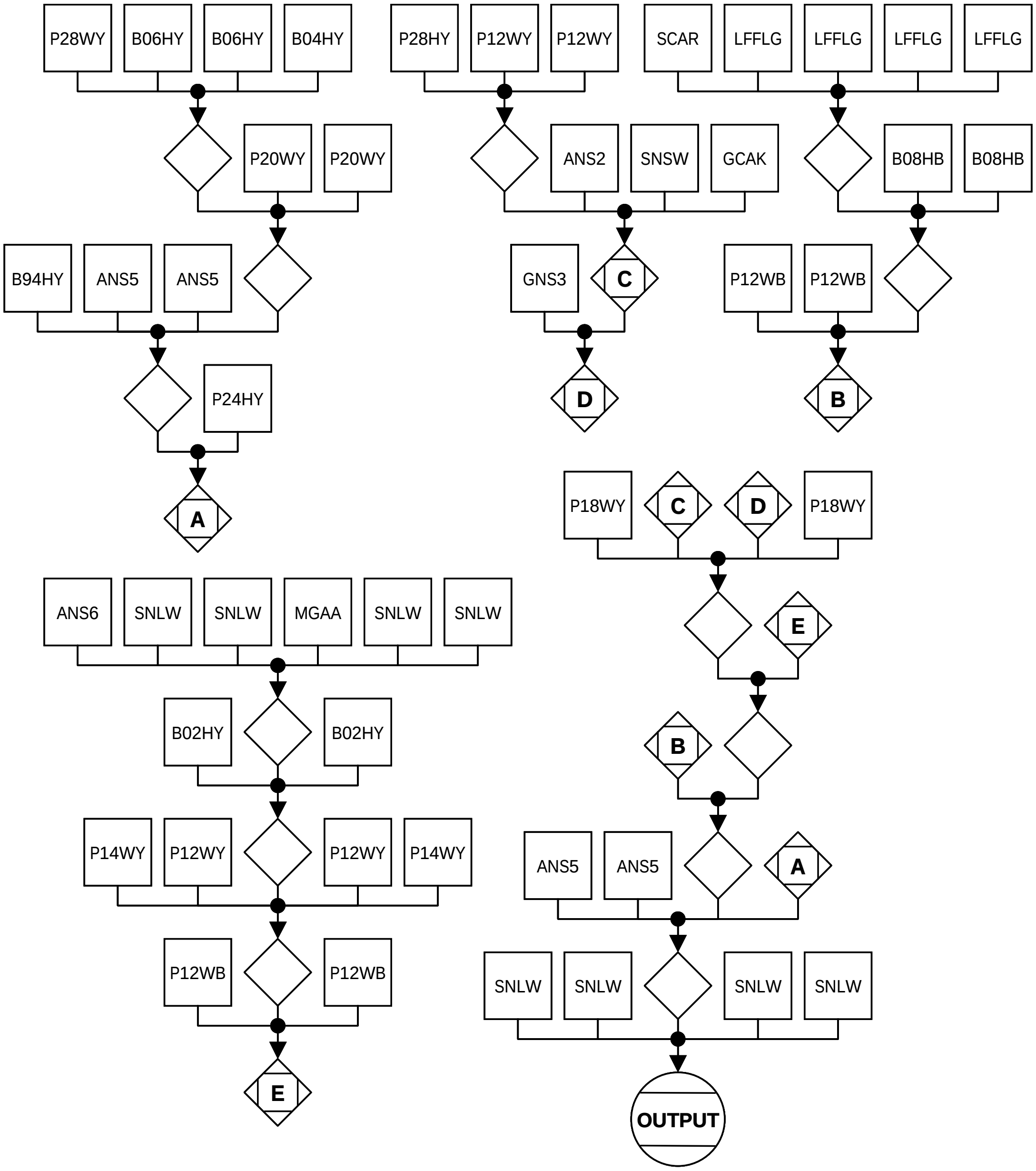

Figure 5: *The Rotational Subsystem Holarchy*.

An important note to be stressed is that the system was constructed entirely having a holarchy in mind; the subsystems are higher-level holons while their constituent elements are lower-level holons. The holonic subsystems, both receive and transmit signals and exchange information with other holons, thus being active agents rather than passive components. The information flows between subsystems are dual to the dependencies in the Gantt chart of the main system schedule. The combined operation of the subsystems was the result of repeated examinations and fine-tuning, in order to coordinate the handling of the product and its conveyance between subsystems.

The entire system required 694 distinct elements for its construction. This number was large because in many cases there were used smaller bricks or plates at the lack of larger ones; hence, the availability in abundance of certain elements would lead to the decrease of the total number of elements used. At the same time, the availability of elements in standard dimensions, dictated the use of multiple elements to develop one element of the same category at a customizable size. The availability of elements at all dimensions would decrease the total number even further; however, this would necessitate a higher production cost for these elements and a significant overhead in coding.

5. CONCLUSIONS

The present work examined the possibility of development of flexible manufacturing systems based on the holonic theory. In particular, the development of subsystems in a more complex whole followed a hierarchical structure, where the component elements themselves are active units in the hierarchy transmitting and receiving information among them, rather than passive units. The overall system was constructed with LEGO blocks. In order to be able to assemble the blocks into functioning structures, each block was coded in a coherent way through a special grammar that was developed for that purpose, and assembly rules in the form of coded instructions from a library were created. The system was then tested and scheduled. The system proved to be robust, flexible and expandable. The presented results indicate a promising research direction, as was also mentioned by other researchers [6,7]. The need to produce rapidly flexible, functional, modular and cost-effective manufacturing systems is a strong initiative for the industry in general; these results, however, are not confined in systems development but may easily be expanded in the development of flexible products. It is essential towards this direction to organize systematically a library of assembly rules, to standardize the codification of the elements, and to profit of the identification of properties of each subsystem. The automation of the generation of assembly alternatives through genetic algorithms emerges as a promising path.

6. REFERENCES

[1] Bongaerts L., Valckenaers P., Brussel H.V., Peeters P., "Schedule Execution in Holonic Manufacturing Systems", in *Proceedings of the 29th CIRP International Seminar on Manufacturing Systems,* May 11-13, 1997, Osaka University, Japan.

[2] Bongaerts L., Wyns J., Detand J., Brussel H.V., Valckenaers, "Identification of Manufacturing Holons", in *Proceedings of the European Workshop for Agent-Oriented Systems in Manufacturing,* pp. 55-73, Berlin, 1996.

[3] Emiris D.M., Koulouriotis D.E., and Bilalis N.G., "Functional Analysis and Synthesis of Modular Manufacturing Systems using the Holonic Theory: Application to Integrated Robotic Workcells", *Digital Enterprise Challenges, Life-Cycle Approach to Management and Production,* pp. 325-336, 2001.

[4] Huang C.C., Kusiak A., "Modularity in Design of Products and Systems", *IEEE Transactions on Systems, Man and Cybernetics*, **28**(1), January, 1998.

[5] Koestler A. *The Ghost in the Machine*. Hutchinson & Co, London, 1967.

[6] Matsuda M., Naoda Y., and Kimura F., "Preliminary Design Support for Mechanical Products Based on Functional Requirements and Modular Concepts Using Genetic Algorithms", *Proceedings of the Fifth IFIP Working Group 5.2, Workshop on Knowledge Intensive CAD,* pp. 47-61, 2002.

[7] Naoda Y., Matsuda N., and Kimura F., "Total Support from Preliminary Design to Assembly Planning for Mechanical Products based on Functional Requirements and Modular Concepts", *Proceedings of the 35th CIRP-International Seminar on Manufacturing Systems*, pp. 512-517, 2002.

[8] Valckenaers P., Van Brussel H., Boneville F., Bongaerts L., and Wyns J., "IMS TEST CASE 5-Holonic Manufacturing Systems", *IMS' 94, IFAV Workshop,* Vienna, 13-15 June, 1994.