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Digital Fabrication Production System Theory: towards an integrated environment for design and production of assemblies

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***Abstract*—This paper introduces the concept and challenges of a Digital Fabrication Production System; a set of processes, tools, and resources that will be able to produce an artifact according to a design, fast, cheap, and easy, independently of location. However, evaluating feasibility of a Digital Fabrication project has two main problems: first, how to evaluate assemblability of the design; second, how to evaluate performance of the supply chain. This paper introduces a methodology to address these problems that combines Network Analysis to evaluate assembly structure with System Dynamics to evaluate supply chain performance.**

***Key Words*—Digital Fabrication, Production System, Supply Chain, System Dynamics.**

I. INTRODUCTION

A Digital Fabrication Production System (DFPS) is a decentralized top-down network of fabrication, distribution and assembly processes that use digitally controlled tools and resources to produce an artifact according to a given design at a specified location, time, and cost. A DFPS project is a complex assembly of custom parts that is delivered by a network of fabrication and assembly processes [1].

Supply chain costs depend on flow and travelled distance in the distribution network: the greater they are, the more expensive the production is. In addition, the broader the supply chain network, the more vulnerable it is to errors since it is slower to respond. Optimizing a supply chain therefore means minimizing number and length of trips and coordinating processes to avoid delays.

A DFPS has a top-down workflow: begin design process with a custom geometric form; decompose it into constructible parts; send the part files for fabrication; transport all parts at the construction site; finally, assemble the artifact. Conceptually it means that based on a well structured supply chain a DFPS can build anything, anywhere, anytime, at controllable cost and quality.

However how can a DFPS build at remote locations while keeping supply chain costs and risk low? Since sending information is much cheaper than transporting materials, a reasonable suggestion seems to be to setup spontaneous *local* supply chains and *remotely* manage them. To avoid local competition, a DFPS should first employ a universal fabrication & assembly strategy and second, universally available materials.

Unfortunately, current reality in Digital Fabrication (DF) projects takes a completely different direction: special materials, complex detailing, long supply chains. As a consequence, DF projects take more time, get more expensive, and involve greater risk than what was planned, making them too complex to plan, understand, and manage. Moreover, most of these problems are discovered during production when it is already late for corrective actions.

This paper deals with the following problem: How can we define a formal method to evaluate the difficulty of production of an artifact if we know the artifact's design and the production system's structure? This paper approaches this problem from two directions: first, assemblability assessment of design; second, feasibility assessment of production flow.

A. Background

Assembly structure in Architecture has mostly been studied by empirical methods on two main directions: CAD modeling (3D, 4D) and Physical Mockups.

1) Previous Work in Architecture

3D CAD modeling of assemblies is based on an *assembly file* that includes individual *part files*. The design methodology is called constrain-based design and is based on constraining the part models inside the assembly model. However, studying assemblies in CAD is inadequate for two main reasons: first, a CAD model may have any structure of constraint delivery, but an assembly has always one. Second, CAD modeling represents the final *state* of the assembly, when all parts have been put together, but not the process of putting these parts together. 4D CAD modeling has been used for clash detection during assembly sequence. However, 4D modeling fails similarly to describe actual constraint delivery between parts. Moreover, CAD 4D is not able to define a proper assembly sequence. As a consequence, by studying a CAD model, the designer cannot tell if an assembly design might be assembled, nor he can make any estimation of the difficulty of the assembly sequence.

Physical mockups have been used during design development to test assemblability. However, there is a significant loss in time and cost. Moreover, in this fashion, testing is empirical, understanding the solution to the geometrical problem is obscure, and design development becomes intuitive. Clearly, designers need efficient tools to study and evaluate assemblies.

2) Previous Work in Product Development and Industrial Management

Assembly structure has been studied in Product Development, and Manufacturing using Network Analysis methods such as the *liaison graph* [2], [3] and the Design Structure Matrix [4], [5]. The liaison graph is a directed acyclic graph whose nodes represent parts and arcs represents liaisons. Direction of arcs indicates order of constraint delivery between two different parts. In a liaison graph no cycle is allowed since that would mean that a part constrains itself through a chain of constraint deliveries.

Performance of systems has been studied in Industrial Management using *System Dynamics*. System Dynamics [6], [7] is a methodology coming from Control Theory, for studying the behavior in time of complex feedback systems. A System Dynamics model is a bipartite network consisting of states (stocks), actions that affect the states (flows) and decision variables that control the actions. System Dynamics has been extensively used to simulate supply chain performance.

While Network Analysis provides a concise and formal way to study systems' structure and System Dynamics provide an effective way to simulate systems' performance it is not clear how a liaison graph could provide information on a System Dynamics model of an assembly process.

B. Proposal

This paper employs Attribute Process Methodology (APM) [8]; a method for assessing feasibility of a DFPS project that combines Network Analysis to evaluate assemblability of the design with System Dynamics to evaluate performance of the supply chain.

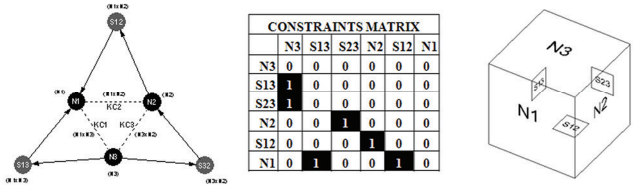
C. Theory

1) Assembly Definition

An *assembly* is a *system* of parts connected through liaisons, the goal of which is to deliver one or more *key characteristics (KC)*. A KC is a requirement that the assembly must meet such as a minimum distance between two parts [2].

2) Assembly Description

Assembly structure is described through the liaison graph and the corresponding *adjacency matrix*. The adjacency matrix of a liaison graph with n nodes is an n*n matrix whose columns and rows represent the nodes of the network.



CONSTRAINTS MATRIX						
	N3	S13	S23	N2	S12	N1
N3	0	0	0	0	0	0
S13	1	0	0	0	0	0
S23	1	0	0	0	0	0
N2	0	0	1	0	0	0
S12	0	0	0	1	0	0
N1	0	1	0	0	1	0

Fig. 1. The liaison graph and adjacency matrix of an assembly of 6 interlocking planar parts.

A mark in column i and row j represents a link from node i to node j. This means that in order to find the precedents of node j we first trace row j and record all marks that we find; then we identify the nodes that correspond to the columns of these marks. Similarly, to find the decedents of node j we have to trace column j and record the rows that correspond to marks that we find. The number of connections that a node has with other neighbor nodes is called the *degree* of the node. If the network is directed, then each node has an in-degree and an out-degree.

II. MATERIALS AND METHODS

This paper deals with assemblies of planar, perpendicularly interlocking parts (Fig. 2). However the theory can be applied to other types of assemblies. The following section describes how to define an assembly sequence, evaluate it, and use it as input in a System Dynamics model.

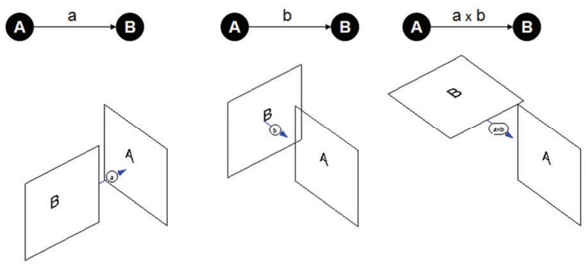


Fig. 2. The 3 possible liaisons between planar parts and their representation in the liaison graph: in the first from left, the installation vector is the normal vector of part A; in the middle, the installation vector is the normal vector of part B; in the third, the installation vector is the cross product of parts A, B.

A. *Defining an Assembly Sequence*

An assembly sequence is a valid way to trace the liaison graph from precedent nodes to decedent nodes starting from a root node. Validity is determined by connectivity rules that have been explained by the author in [9]. A root node is a node that has no precedents. The difficulty of each step relates to the in-degree of the node which indicates the number of simultaneous liaisons that must be achieved during that step. For example, a part will be more easily connected to another part if it has one liaison rather than if it has multiple liaisons. Therefore, the in-degree distribution along an assembly sequence indicates the difficulty of the assembling process.

In the adjacency matrix an assembly sequence can be represented as an ordering of the rows and columns. Such ordering can be derived by rearranging the rows and columns of the adjacency matrix so the resulting matrix has all its marks below the diagonal. The sequence of the sums of each column gives the in-degree distribution of the assembly sequence.

B. *Dynamic analysis of an assembling system*

This paper proposes a System Dynamics implementation to measure performance of an assembling process in executing an assembly sequence as a series of nodes. Two stocks, the start stock and the end stock, describe the level of achieved liaisons in the system. In the beginning of the simulation the level of the start stock is zero because no part is assembled yet. In the end of the simulation, the level of the end stock is equal to the total number of links in the liaison graph, because all parts have been assembled. The flow that changes the two levels is controlled by the assembling rate. If the average assembling time per part is fixed, then the assembling rate will fluctuate according to the in-degree distribution sequence which denotes the difficulty of the assembly sequence. For example, an in-degree distribution of [0,1,1,2] means that the first part needs no liaisons (root), the second, and the third parts need 1 liaison each, and the fourth part needs 2 liaisons to be assembled. More refined System Dynamics models that include learning factors, error factors, etc. can be built starting from this basic structure.

C. *Experiment: Structural and dynamic analysis of Façade Panel's assembly*

The following experiment refers to the design, fabrication, and assembly of a mockup of a façade panel (Fig. 3). Design development took place in a parametric 3D CAD modeling software (CATIA V5 R18). The assembly was successful; however it proved to be difficult, and took significantly more time than the designer expected.

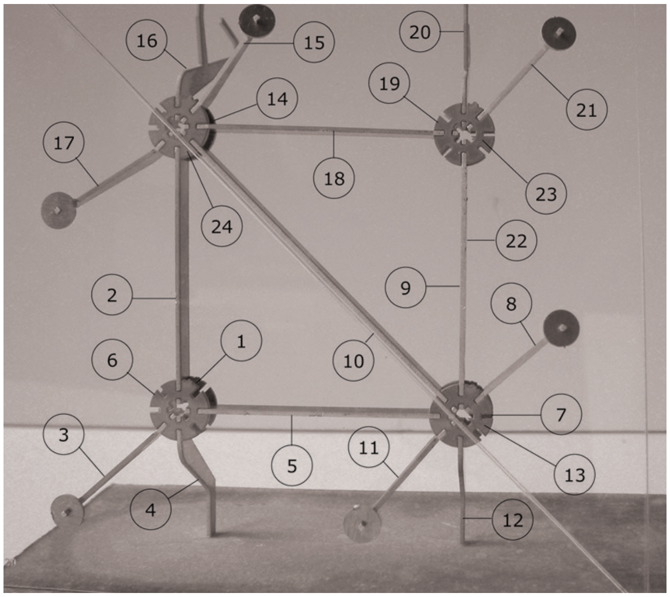


Fig. 3. Physical prototype of an aluminum façade panel fabricated in water jet.

While this example is relatively simple, including a small number of parts, it clearly demonstrates the lack of tools that designers need to understand assembly process.

A representation of the assembly with the liaison graph (Fig. 4) and the adjacency matrix (Fig. 5) shows that while the assembly is possible, there are two steps in the assembly sequence of high difficulty because they require simultaneous liaisons.

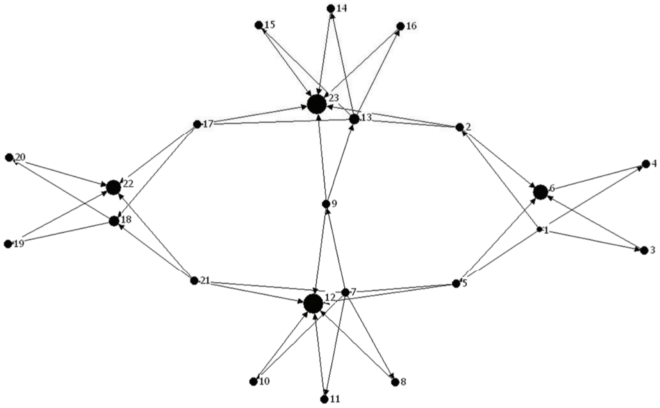
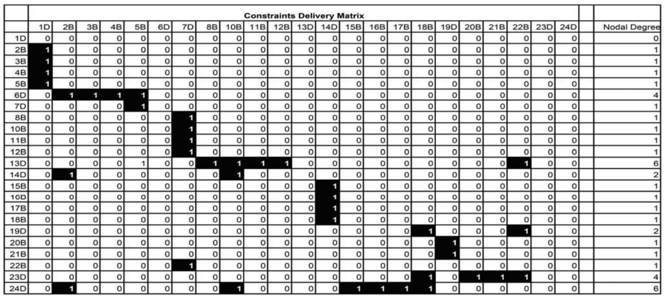


Fig. 4. The liaison graph of the façade panel. Size of nodes is proportional to the in-degree, showing difficulty of assembly step.



	Constraints Delivery Matrix																								
	1D	2B	3B	4B	5B	6D	7D	8B	10B	11B	12B	13D	14D	15B	16B	17B	18B	19D	20B	21B	22B	23D	24D		Nodal Degree
1D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
2B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
3B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
4B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
5B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
6D	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		4
7D	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
8B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
10B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
11B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
12B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
13D	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0		6
14D	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2
15B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
16B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
17B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
18B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
19D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0		2
20B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0		1
21B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0		1
22B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
23D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0		4
24D	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0		6

Fig. 5. The adjacency matrix of the façade panel rearranged according to the followed assembly sequence.

The nodal degree distribution along the actual assembly sequence (Fig. 6) shows the difficulty of each step as a function of the number of connections that have to be achieved with the rest of the assembled artifact.

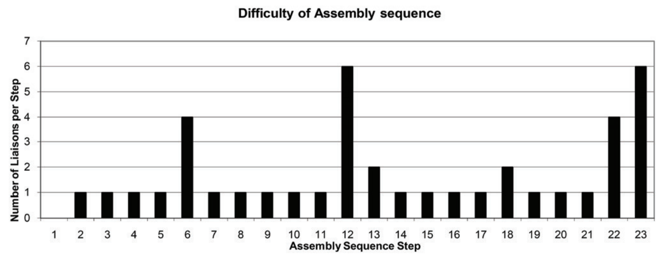


Fig. 6. The nodal degree distribution of the assembly sequence that was actually followed. The degree distribution chart shows that 12th and 23rd steps are the most difficult.

The nodal degree sequence is then inserted as input in the simple System Dynamics model that represents the assembling process. The model clearly shows that assembling rate will significantly drop at the 12th and 23rd step of the assembly sequence.

1) Explanation of the System Dynamics model

The structure of the System Dynamics model consists of two stocks, the *Parts to be Assembled* and the *Assembled Parts* (Fig. 7). Parts move from one stock to the other through the *Assembling Rate*; the faster the *Assembling Rate*, the less time will take for the assembly to be completed.

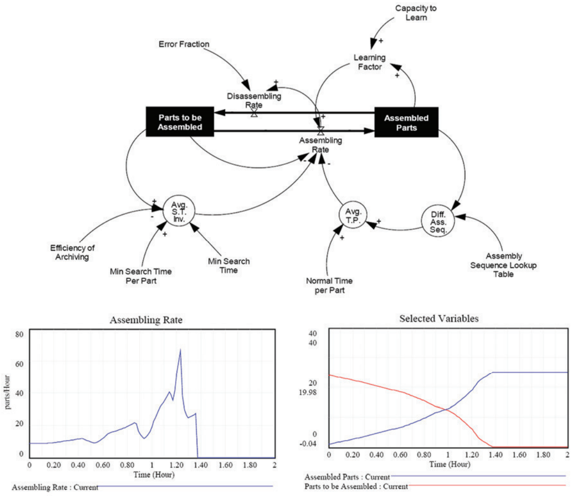


Fig. 7. System Dynamics model of the assembly sequence and simulation graphs: the left graph shows the average time per part during assembly; the right graph shows the level of the two stocks during the simulation.

However, due to errors some parts will need to be disassembled and reassembled. Therefore there is a *Disassembling Rate* that removes parts from the *Assembled Parts* stock back to the *Parts to be Assembled* stock.

The *Assembling Rate* depends on the following factors: first, the *Learning Factor* and the *Capacity to Learn.* Second, the *Average Search Time in Inventory (Avg.S.T.Inv);* average search time depends on *Efficiency of Archiving,* which is how well organized the parts are in the inventory. Third, on the difficulty of the assembly sequence that is given by the Assembly Sequence Lookup Table. The lookup table returns the in-degree of each step of the assembly sequence. The Disassembling Rate depends on the Error Factor and on the Assembling Rate.

D. Generalization: Mapping & Simulating Supply Chain structure

Generalizing, similar principles to the ones applied in the liaison graph and the assembly sequence evaluation can be applied to the entire supply chain network. As the assembly sequence describes the way according which the assembling processes will collaborate to assemble the artifact, similarly the task sequence describes the order which the production processes will collaborate to bring the parts to the construction site. It should be obvious that the assembly sequence graph is just a specialization of a task sequence graph; in fact, it is the final branch of the task sequence graph. Starting from the liaison graph and following a reverse order we can map the entire supply chain structure (Fig. 8).

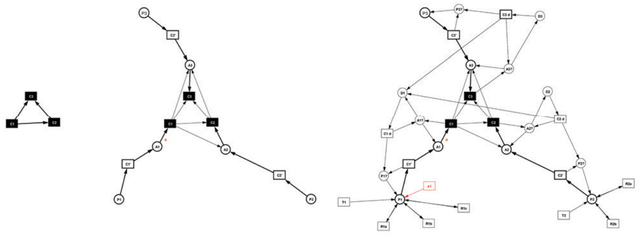


Fig. 8. Starting from the liaison graph the entire supply chain can be mapped as a process-state diagram.

III. RESULTS AND DISCUSSION

Application of network analysis methods to evaluate assemblability of a design is a significant help during design process. The analysis can start before the final CAD model is finished since the liaison representation uses the normal vectors. In the experiment the presented method was successful in revealing information that cannot otherwise be studied with typical digital modeling techniques. This paper showed that we can use metrics from a network model such as the liaison graph to include them in a System Dynamics model. Points in the process of high difficulty were located and they would be valuable if the designers followed this methodology during design. Modeling of a supply chain for a construction project can be a tedious work. This partly because of the effort needed to convert the information into attributes and processes.

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