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GRAPH PARTITIONING TECHNIQUE TO IDENTIFY PHYSICALLY INTEGRATED DESIGN CONCEPTS

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ABSTRACT

This study proposes a graph partitioning technique based on edge weights to accomplish the physical integration of parts as proposed in Axiomatic Design. According to the physical integration concept, the design features should be integrated into a minimum number of parts in order to reduce information content and thus increase the probability of a successful design, given that the independence of functional requirements is still satisfied. However, no specific method is suggested in the literature for determining the optimal degree of physical integration of a design artifact. This is particularly important with the current advancement in Additive Manufacturing technologies. Since additive manufacturing allows physical elements to be integrated, new methods are needed to help designers evaluate the impact of the physical integration on the design success. The objective of this paper is to develop a framework for determining the best way that functional requirements can be assigned to different parts of a product.

Keywords: Physical Integration, Axiomatic Design, Additive Manufacturing, Graph Partitioning

1 BACKGROUND

Axiomatic Design (AD) was developed by MIT mechanical engineering professor Num P. Suh in 1976 and was the first to coin the idea of independence of functional requirements. The primary focus of AD is on mapping the problem into several domains (e.g. customer domain, functional domain, physical domain, and process domain), to enable designers to check the axioms and select the best design solution [1]. The first step in designing a system is to define a set of Functional requirements (FRs). The minimum set of independent requirements that the design should satisfy is considered the set of FRs. The next step is to map the set of FRs into the physical domain, or a set of Design Parameters (DPs). Once DPs are determined based on design embodiment principles, designers consider the process domain and identify the Process Variables (PVs). PVs often act as constraints in the system, since designers are not free to change the existing manufacturing processes [2].

Based on the philosophy that good designs share the same characteristics regardless of their physical nature or their domain of application, Suh attempted to root the engineering design process in two main axioms: (1) Independence Axiom and (2) Information Axiom. According to the independence axiom, FRs (which represent the goals of a design) must remain independent. To satisfy FRs, a set of DPs is chosen. According to the Independence axiom, DPs must be chosen such that the independence of FRs is maintained [3]. Based on the independence axiom, if one of DPs failed, not all functional requirements would be affected. The Independence axiom is based on the concept of changing multi-input/multi-output systems into a set of one-input/one-output systems to maintain the independence of FRs. The aim of information axiom is to minimize the complexity of the system or the information content [3].

What is important in AD is that the design derived from the mapping process must satisfy the Independence Axiom, meaning that the FRs should be satisfied independently with a set of DPs. AD uses design matrices to relate FRs to DPs and represents the design using a set of equations. What makes Axiomatic Design powerful is that it provides a quantitative approach to the formation of normative theories of design [4]. The relationship between the FRs and the DPs is characterized as follows:

$$\{FR\} = \{A\}\{DP\} \tag{1}$$

Where each element of Matrix A, Aij, connects a component of the FR vector to a component of the DP vector [5]. The characteristics of design matrix A determine the degree in which the proposed design satisfies the Independence Axiom (Figure 1). For example, a diagonal matrix is an ideal matrix, where each FR is independently satisfied by one corresponding DP (uncoupled design). In the case of a full matrix (coupled design), the design violates the Independence Axiom since the change of any DP has an impact on all FRs. The independence axiom is particularly useful in the case of multi-objective optimization problems, due to the fact that each FR is independently satisfied by a set of design variables [6].

	Uncoupled Design	Decoupled Design	Coupled Design
Design Matrix	$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & 0 \\ A_{2,1} & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} \\ A_{2,1} & A_{22} \end{bmatrix}$

FIGURE 1. Three different forms of design matrices

Since its origination in the late 1970s, Axiomatic Design has been the point of attention in the academic research, has been used widely across many disciplines, and has been taught internationally as part of engineering curricula [7] [8]. In fact, Axiomatic design is known one of the most important engineering developments of the last century [9]. So far, 10 international conferences on Axiomatic Design have been held in countries around the world, with the last one in Xi'an, China, September 21–24, 2016. In addition to the field of engineering design, AD has impacted a wide range of practices in other disciplines including but not limited to: healthcare delivery systems [10], software design [11], production scheduling [12], manufacturing system design [13], supplier selection [14], interactive art [15], decision science [16], and additive manufacturing [17]. There are, however, several flaws in Axiomatic Design, including the point that there is no structured method available for generating design matrices based on the axioms and the two axioms do not sufficiently capture all that is needed in the design (e.g., human aspects of design [18], consumer preference, market demand [19], manufacturing considerations, and the potential to force a preference structure on designers [20].

However, one main challenge about AD is that the concept of coupled design is very confusing to practitioners. Often designers believe that a simple design is a good design. From this belief, we may conclude that a coupled design in which one DP satisfies multiple FRs is preferred [5]. However, the Independence Axiom does not mean that the DPs must be independent nor that each DP must correspond to a separate physical part. For example, a bottle-can opener is designed to satisfy two FRs and has more than 10 DPs, but has only one piece (Figure 2). It should be noted that the concept of physical integration is completely different from modular design. Module is defined as a part or a group of parts that can be dismantled from the product in a non-destructive way as a unit [21, 22]. Ishii et al. [23] have referred to modular design as minimizing the number of functions per part. According to Ulrich and Eppinger [24] the most modular design is one in which each function is implemented by exactly one module or subassembly and there are limited interactions between modules.

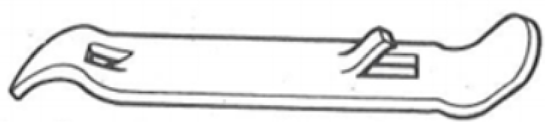

FIGURE 2. Bottle-can opener: An example of a physically integrated device that satisfies two functional requirements [25]

With the focus on physical integration of multiple design features integrated into a single part, researchers have come up with various complexity quantifying methods. Decomposition of FR- DP can result in concrete process variables, which is very much essential for practically applicable solutions. Further, this PVs can be integrated with CAs. But most of the complexities have been resorted between FR and DP [26–28]. There are several existing complexity quantifying methods. The concept of changeability and the use of Axiomatic Design when designing production equipment are first introduced. Second, design-solution-specific barriers to flexibility and changeability are described [29, 30].

However, the idea behind *physical integration* or physical coupling is to integrate more than one FR in a single component, as long as FRs remain independent. Therefore, physical integration reduces the design complexity (at least in the physical domain). *While designers are in favor of physical integration, there is no normative approach on how to achieve physical integration using scientific engineering design techniques*.

Graph theory algorithms are widely used in making design decisions [31–33]. Buluc et.al [34] discussed the way that graph partitioning is effective in analyzing complex networks. Division of graphs into small partitions is the primary step for making algorithmic operations more efficient. One of the important substeps for complexity reduction or parallelization is graph partitioning. Large graphs are first partitioned into small ones and then they are analyzed. This is highly helpful in simulations, social networks or road networks.

Different graph partitioning techniques may be used but the approaches are based on some certain basic algorithms [35]. With the current evolving technology, multiple graph partitions can be run in parallel and complex systems can be analyzed [36, 37]. To name a few studies and different applications of graph partitioning methods, Li et al. [38] used the graph partitioning techniques to extract reusable 3D CAD models to improve design reusability. Borisovsky et al. [39] worked on a machining line design problem which has sequences of workstations equipped with processing modules called blocks each of which performs specific operations. They used a graph partitioning technique to integrate machines to perform different sets of operations. Biologists have used the graph partitioning technique that we have adopted to study the RNA structures. They analyzed the best possible RNA configurations that are stable using the Laplacian Eigen values and vectors [40]. We have used this graph partitioning approach using a proposed ranking system for functional requirements to bring in the concept of physical integration in design.

Integrating functional requirements facilitates fewer assembly parts, greater flexibility, and less logical efforts. EOS, a Manufacturer in Germany has used additive manufacturing technology for physically integrating the parts. They wanted to achieve integration of a maximum number of FRs with a minimum number of parts. EOS printed their centrifuge washing rotor using this concept. The traditionally manufactured parts with 32 assembly parts were reduced to 3 assembly parts (2 of them were printed). The structure intermeshing largely helped in reducing complexity and assembly time [41].

The objective of this paper is to provide some background information about the concept of physical integration and open a new venue for determining the best level of physical integration, particularly for additively manufactured parts that have less manufacturing constraints in terms of geometry and shape. The graph theory helps us find the best pair of FRs that can be combined to achieve a more feasible design.

REFERENCES

[1] Shirwaiker, R. A., and Okudan, G. E., 2008. "Triz and axiomatic design: a review of case-studies and a proposed synergistic use". *J. Intell. Manuf.,* **19**(1), Feb, pp. 33–47.

[2] Suh, N. P., 1998. "Axiomatic design theory for systems". *Research in Engineering Design,* **10**(1), pp. 189–209.

[3] Suh, N. P., 2016. *Challenges in Designing and Implementing Large Systems (Overcoming Cost Overruns and Missed Project Schedules)*. Springer International Publishing, Cham.

[4] Farid, A. M., and Suh, N., 2016. *Axiomatic Design in Large Systems: Complex Products, Buildings and Manufacturing Systems*. Springer.

[5] Park, G. J., 2014. "Teaching conceptual design using axiomatic design to engineering students and practitioners". *Journal of Mechanical Science and Technology,* **28**(3), pp. 989–998.

[6] Hirani, H., and Suh, N. P., 2005. "Journal bearing design using multiobjective genetic algorithm and axiomatic design approaches". *Tribology International,* **38**(5), pp. 481–491.

[7] Tate, D., 2015. "Axiomatic design: Review, impact, and fu-

ture direction". *Advances in Multidisciplinary Engineering,* **15**, p. V015T19A006.

[8] Park, G. J., 2007. *Analytic Methods for Design Practice*. Springer Science & Business Media.

[9] Anonymous, September 21–23 2016. The 10th international conference on axiomatic design. [Online]: `http://icad2016.org`.

[10] Bosire, J., Wang, S., Khasawneh, M., Gandhi, T., and Srihari, K., 2016. *Designing an Integrated Surgical Care Delivery System Using Axiomatic Design and PetriNet Modeling*. Springer International Publishing.

[11] Girgenti, A., Giorgetti, A., Citti, P., and Romanelli, M., 2015. "Development of a custom software for processing the stress corrosion experimental data through axiomatic design". In Procedia, Vol. 34, CIRP, pp. 250–255.

[12] Cochran, D. S., Eversheim, W., Kubin, G., and Sesterhenn, M. L., 2000. "The application of axiomatic design and lean management principles in the scope of production system segmentation". *International Journal of Production Research,* **38**(6), pp. 1377–1396.

[13] Fan, S. H., Li, J. H., Jiang, Z. B., and Zhang, Z. G., 2014. "Axiomatic design of facility layout for reconfigurable manufacturing system". *Applied Mechanics and Materials,* **703**, pp. 273–276.

[14] Zarali, F., and Yazgan, H. R., 2016. "Solution of logistics center selection problem using the axiomatic design method". *World Academy of Sciences, Engineering and Technology, International Journal of Computer, Electrical, Automation, Control and Information Engineering,* **10**(3), pp. 489–495.

[15] Foley, J. T., and Harðardóttir, S., 2016. "Creative axiomatic design". In Procedia, Vol. 50, CIRP, pp. 240–245.

[16] Fan, L. X., Cai, M. Y., Lin, Y., and Zhang, W., 2015. "Axiomatic design theory: Further notes and its guideline to applications". *International Journal of Materials and Product Technology*.

[17] Salonitis, K., 2016. "Design for additive manufacturing based on the axiomatic design method". *TheInternational Journal of Advanced Manufacturing Technology*, pp. 1–8.

[18] Maier, J. R. A., and Fadel, G. M., 2009. "Affordance based design: A relational theory for design". *Research in Engineering Design,* **20**(1), pp. 13–27.

[19] Hazelrigg, G. A., 2003. "Validation of engineering design alternative selection methods". *Engineering Optimization,* **35**(2), pp. 103–120.

[20] Olewnik, A., and Lewis, K., 2005. "On validating engineering design decision support tools". *Concurrent Engineering: R&A,* **13**, pp. 111–122.

[21] Allen, K. R., and Carlson-Skalak, S., 1998. "Defining product architecture during conceptual design". In Proceedings of the 1998 ASME Design Engineering Technical Conference, Atlanta, GA.

[22] Gershenson, J. K., Prasad, G. J., and Zhang, Y., 2003. "Product modularity: Definitions and benefits". *Journal of Engineering Design,* **14**(3), pp. 295–313.

[23] Ishii, K., Juengel, C., and Eubanks, C. F., 1995. "Design for product variety: Key to product line structuring". In Proceedings of the 1995 ASME Design Engineering Technical Conferences: $7^t h$ International Conference on Design Theory and Methodology, The American Society of Mechanical Engineers.

[24] Ulrich, K., and Eppinger, S. D., 1995. *Product Design and Development*. McGraw-Hill.

[25] Suh, N. P., 1990. *The Principles of Design*. Oxford University Press, New York.

[26] Guenov, M. D., and Barker, S. G., 2005. "Application of axiomatic design and design structure matrix to the decomposition of engineering systems". *Systems engineering,* **8**(1), pp. 29–40.

[27] Eppinger, S. D., and Browning, T. R., 2012. *Design Structure Matrix Methods and Applications*. MIT press.

[28] Ş. T. Pektaş, and Pultar, M., 2006. "Modelling detailed information flows in building design with the parameter-based design structure matrix". *Design Studies,* **27**(1), pp. 99–122.

[29] Tang, D., Zhang, G., and Dai, S., 2009. "Design as integration of axiomatic design and design structure matrix". *Robotics and Computer-Integrated Manufacturing,* **25**(3), pp. 610–619.

[30] Foith-Förster, P., Wiedenmann, M., Seichter, D., and Bauernhansl, T., 2016. "Axiomatic approach to flexible and changeable production system design". In Procedia, Vol. 53, CIRP, pp. 8–14.

[31] Zetterberg, A., Mörtberg, U. M., and Balfors, B., 2010. "Making graph theory operational for landscape ecological assessments, planning, and design". *Landscape and urban planning,* **95**(4), pp. 181–191.

[32] Bondy, J. A., and Murty, U. S. R., 1976. *Graph Theory with Applications*. Citeseer.

[33] Papalambros, P. Y., 1995. "Optimal design of mechanical engineering systems". *Journal of Vibration and Acoustics,* **117**(B), pp. 55–62.

[34] Buluç, A., Meyerhenke, H., Safro, I., Sanders, P., and Schulz, C., 2016. *Recent Advances in Graph Partitioning*. Springer, pp. 117—158.

[35] Schulz, C., May 20, 2016. Graph partitioning and graph clustering in theory and practice. [Online]: `http://algo2.iti.kit.edu/schulz/gpgc_vorlesung/graphpartitioning_lecture.pdf`.

[36] Fern, X. Z., and Brodley, C. E., 2004. "Solving cluster ensemble problems by bipartite graph partitioning". In Proceedings of the Twenty-First International Conference on Machine Learning, ACM, p. 36.

[37] Hendrickson, B., and Kolda, T. G., 2000. "Graph partitioning models for parallel computing". *Parallel computing,* **26**, pp. 1519–1534.
[38] Li, M., Zhang, Y. F., and Fuh, J. Y. H., 2010. "Retrieving reusable 3d cad models using knowledge-driven dependency graph partitioning". *Computer-Aided Design and Applications,* **7**(3), pp. 417–430.
[39] Borisovsky, P., Dolgui, A., and Kovalev, S., 2012. "Algorithms and implementation of a set partitioning approach for modular machining line design". *Computers & Operations Research,* **39**(12), pp. 3147–3155.
[40] Kim, N., Zheng, Z., Elmetwaly, S., and Schlick, T., 2014. "Rna graph partitioning for the discovery of rna modularity: A novel application of graph partition algorithm to biology". *PloS one,* **9**(9), p. e106074.
[41] EOS, 2019. Functional integration. [Online]: `https://www.eos.info/functional-integration-39f837a0e69ec898`. [Accessed]: July 12, 2019.