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Developing a TRIZ-based Design for Flexibility Tool for Manufacturing Facilities

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Abstract

As manufacturers evaluate assets and long-term production plans, they struggle with how best to meet complex building requirements that maximize building flexibility and minimize costs. Research shows that manufacturers highly prioritize facility flexibility. However, infusing flexibility into facility design can be complex and achieving it can be costly. These issues could be mitigated with a dedicated tool for addressing flexibility in facility design. TRIZ (Theory of Inventive Problem Solving) is a problem-solving method that exploits information contained in millions of patents to identify solution genres and standard contradictions to drive inventive design principles. This user-friendly, decision support tool can efficiently reduce the complexity of incorporating flexibility into manufacturing facility design. Using this tool as a platform and incorporating information from fifteen case studies, construction-specific terms were mapped to TRIZ parameters and principles to create a construction industry specific TRIZ contradiction matrix. This paper describes basic TRIZ theory and previous uses in the construction industry. It then discusses industry input and case studies that helped make it construction-specific. Finally, it addresses the modified TRIZ tool's potential benefits to the construction industry regarding flexibility considerations.

Keywords
Flexibility, Manufacturing, Building Design, TRIZ, Construction

1. Introduction

Twenty-first century global economic needs change on an almost daily basis, and industrial engineers in the construction industry are faced with the ever-more-challenging task of predicting, planning, and investing in businesses in ways that maximize company profits and meet societal expectations. The U.S. Bureau of Labor and Statistics reports that over 100,000 industrial engineers within the construction industry are employed as construction, architectural, and engineering managers, business operations specialists, and industrial engineers [1]. They are called upon as partners by their counterparts in manufacturing to help assess company assets and long-term production plans, with the goal of meeting both short- and long-term production needs. Many manufacturers have extremely complex products, processes, and/or life cycles, and manufacturers struggle with how best to meet the complex facility requirements necessary to maximize lifetime facility costs, particularly when faced with changes in manufacturing process technologies, evolving product lines, and fluctuating market demands [2]. Besides complexity and the non-standard production of construction projects, challenges such as tight construction schedules and low profit margins also add to the difficulty of designing and then building or repurposing manufacturing facilities in a way that meets both construction and manufacturing business needs [3]. To remain profitable, manufacturers must be able to respond to markets quickly [4]; this requires quick facility redesign, ideally afforded by already built-in facility flexibility.

Historically, manufacturers often re-purpose or build new facilities to produce new product, which delays time to market. In the 2013 white paper, "Designing Flexibility into the Industrial Workplace," the Industrial Asset Management Council (IAMC) and the Society of Industrial & Office Realtors (SIOR) summarized 63 survey responses from U.S.-based manufacturing companies, including companies like Caterpillar, BASF, and Bristol-Myers Squibb. They reported that 84% of manufacturers identify facility flexibility and re-use potential as issues, with costs of repurposing ranging from \$2-\$750 per square foot [4]. The biggest barriers to production flexibility vary across industries; for example, 40% of the light manufacturing respondents said facility layout is their primary obstacle to flexibility, while heavy and regulated (e.g., pharma) manufacturers reported that workflow is their biggest barrier [4].

Facility flexibility, defined by Maslak et al. as "time-to-market sensitive building (or facility) that is responsive to internal and external uncertainty both in the present and in the future, while supporting manufacturing processes with minimal future time and capital investment," [2] is a design criterion that manufacturers can use for balancing uncertainty [5]. Because manufacturing is often highly competitive and carries large economic risks, industries are moving away from traditional single-purpose building designs and toward those that support facility flexibility, and hence process flexibility [2]. However, designing and building flexible buildings has its own barriers, including higher upfront costs, longer completion times, location and layout constraints, and utilities limitations [4]. Predicting future business needs, regulatory issues, and environmental issues is challenging, at best. Gaining management buy-in by quantifying the expected return on investment (ROI) of flexibility investment is also very difficult given these challenges [4].

While infusing flexibility into facility design can be complex and include higher initial costs [2, 6, 7], it also extends a building's useful life and the amount of value that can be realized [8, 9]. According to Saari et al., facility flexibility can be achieved in two different ways. One way is through "modifiability," which refers to the potential of a facility to be used by different users over time (i.e., repurposing). The other is "service flexibility," which is the building's potential for rapid adaptability by the current user [9]. Facilities that can quickly and cost-effectively accommodate various products, processes, and functionalities make companies more competitive and enhance resale potential [4].

Flexible design should be considered at the start of the facility design process to ensure maximum cost-effectiveness, [9], but recent efforts have been inconsistent and largely unstructured [2]. This is partly due to the inherent differences between manufacturing sectors. For example, a pharmaceutical manufacturer has very different processes, product lifecycles, and facility needs from a heavy equipment manufacturer. Because of this, there is no flexible design standard or one-size-fits-all approach [10]. Flexible design concepts like modularity, easy access utility corridors, open design spaces, decentralized HVAC, and prefabricated "plug-and-play" components are well-known in the construction industry, but knowing when to include which concepts in initial facility design to maximize the likelihood of cost-effectiveness is a challenge [2, 11].

Addressing this challenge requires being innovative. However, construction lags behind many other industrial sectors in innovation [12, 13], perhaps due to a lack of efficient tools, a lack of systematic approach [13], or the existence of specialized requirements within the construction industry like regulations [12]. Renev and Chechurin cited a lack of structured theory within the construction industry for managing innovation improvement, as well as a lack of systematic or formal design methods [12]. Some research describes ways to think about construction flexibility. For example, Slaughter identified categories of innovative flexibility considerations, including reducing interactions within inter- and intra-systems, using interchangeable system components, increasing layout predictability, improving physical access and flow, dedicating specific area/volume for system zones, enhancing system access proximity, installing phase systems, and simplifying partial/phased demolition [8]. However, there are limited standardized processes developed for or used by the construction industry to facilitate innovative flexibility design.

One well-regarded tool, prevalent in product and process engineering but less so in the construction industry, is TRIZ. Widely available as a toolkit since 1993, the translated meaning of the acronym TRIZ is "theory of inventive problem solving" [14]. TRIZ combines concepts, methods, and tools developed for innovative and efficient problem-solving based on the analysis of millions of patents [3, 14]. Its effectiveness lies in "not reinventing the wheel." Because it is based on previous solutions, using it systematically reduces the time-to-solution for difficult problems [3, 14]. Previous uses of TRIZ in the construction industry include, but are not limited to, analyzing formwork patents, building facades, heat insulation, and bearing steel [12, 15]. Yu et al. described TRIZ as a "new area of construction innovation." [13] Zhang, et al. identified TRIZ as a key component for developing a knowledge management system to "facilitate the generation of new technologies and processes, which will improve the industry's productivity, profitability, and competitiveness." [3] However, as of 2016, Renev and Chechurin's comprehensive literature review showed that fewer than 2% of all TRIZ-related publications in SCOPUS are related to the construction industry (a total of 28 scientific works related to TRIZ application in construction were identified and reviewed) [12].

An important advantage of TRIZ is "that it can overcome psychological inertia, which represents the barriers against personal creativity and problem-solving ability." [3] It was developed to solve common technical issues across all product and process genres, and consequently doesn't provide specific tools for any given industry [12], but provides engineers a systematic way to generate innovative solutions based on the combined expertise and experience of others [3]. Because innovations across industries and sciences follow a fairly succinct list of inventive principles, the generalized tools of TRIZ can be adapted to specific industries and used relatively simply and predictably [3, 12]. This has been done successfully numerous times for different functions like quality improvement, service, redesign [12, 16], and manufacturing [16] as well as for industries based on chemical engineering, human factors and ergonomics, and construction processes [17, 18]. Practical uses of TRIZ as a tool for identifying efficient solution spaces for facility flexibility design within the construction industry will require nomenclature and content-specific development [12].

Zhang, et al. identified 28 different TRIZ concepts and tools, including those of Contradictions, 40 Inventive Principles for Resolving Technical Contradictions, 4 Principles for Physical Contradiction Elimination, and a Matrix for Resolving Technical Contradictions [3]. Similarly, Gadd described the 39 Technical Parameters and 40 Inventive Principles of TRIZ, which are used to create the Contradiction Matrix [14]. A contradiction is when two important and desired characteristics, or parameters, are at odds with each other [3, 14]. In other words, improving parameter 'A' could cause harm (i.e., decreased functionality or a worsened condition of some kind) to parameter 'B.' As a typical construction example, some indoor spaces require a high percentage of outdoor air pumped inside. Increasing the percent of outdoor air provides better air quality, but also increases energy costs (a less desirable state), thereby causing 'good' to invoke 'harm' (ideally, the goal would be increased air quality with no increased cost). The standard TRIZ contradiction matrix shown in Figure 1 lists parameters that must be improved in rows, and parameters that should not be worsened in columns. Each intersection of parameters lists the principles (solution spaces) identified through patentable (i.e., innovative) solutions.

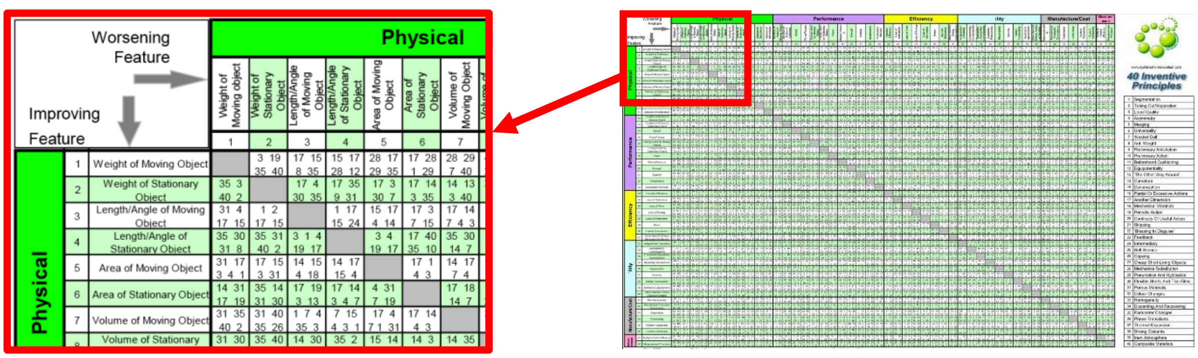


Figure 1. TRIZ Contradiction Matrix, adapted from [16].

Renev and Chechurin identified the contradiction matrix as the most applied tool in construction-related TRIZ literature, stating that based on the current state of research, "it is relevant to adapt such TRIZ tool [sic] as the contradiction matrix to problem solving in construction engineering and management and provide a number of case studies." [12] Likewise, Mann and Catháin lauded the idea of the contradiction matrix as the consolidation of the world's contradiction-eliminating experience. However, they also noted that it doesn't work as intended without industry specific language, and state that "the tool would benefit from a re-framing," (in their case, for architecture) [19]. Zhang, et al. confirmed that the most challenging step in creating a knowledge base is extracting specific knowledge from subject matter and discipline experts, along with transforming general TRIZ solution genres into construction-specific ones [3]. While others have proposed such activities and developed TRIZ-based frameworks related to construction [3, 13], no TRIZ-based contradiction matrix specific to the construction industry for designing and building facility flexibility was found in the literature. Without such a matrix, the full benefit of TRIZ as it relates to innovative solution generation cannot be fully realized.

2. Methods

To address the need for a construction-specific contradiction matrix, facility flexibility needs and construction-specific flexibility language were identified through onsite case studies conducted as part of a cooperative industry and academic undertaking funded by the Construction Industry Institute (CII). Case studies were conducted by a team composed of educators from three universities, and industry representatives including engineers from eight companies and five business owners. Information was collected at fifteen manufacturing facilities across the United States, and across a range of industries, including heavy, light, and regulated manufacturing. Product sectors included consumer products, bio/pharmaceuticals, food/beverage, equipment, chemicals, mechanical parts, and aerospace components.

Case studies and literature were analyzed to identify common contradictions that occur when designing a flexible facility. Examples of facility flexibility garnered from the case studies supported those found in the literature, with both providing functional relevance. No statistical analysis was necessary as successful solutions in the literature and case studies were presented based on frequency. Both technical and physical contradictions were considered for the matrix, including 40 inventive principles and four separation principles respectively [3, 14]. Twenty-three construction-specific parameters were identified and mapped to as many as four of the original TRIZ parameters, dependent upon the broadness or specificity of each parameter, with the mapping process demonstrated in Figure 2.

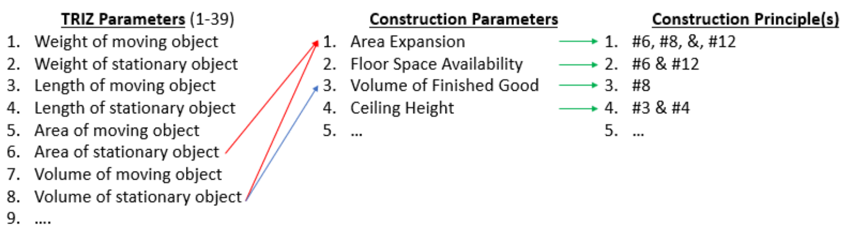


Figure 2. Mapping from Original TRIZ to Construction Industry Terminology

Using a previously created TRIZ matrix tool in Excel as a template [20], the contradiction matrix was revised to include construction-specific parameters and principles, along with construction examples. To further ensure industry-specific language and context, feedback was obtained from CII project team members relevant to parameters, principles, and examples included in the Excel macro contradiction tool. Reduction of principles was considered based on their realistic application to facility design; for example, no construction example for “strong oxidants” could be related to construction flexibility, and it was thus eliminated as a solution principle. Finally, visual examples of each principle were added to help users visualize successful applications.

3. Results and Discussion

The TRIZ Excel macro allows users to input two desired flexibility characteristics and then outputs corresponding TRIZ principles, flexible facility examples, and visuals as a starting place for brainstorming innovative solutions. The process for tool usage is shown in Figure 3:

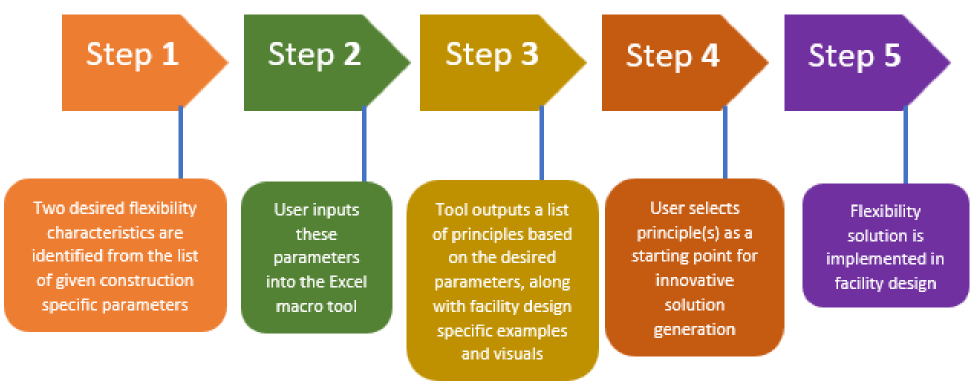


Figure 3. Process for Using Excel-based TRIZ Tool for Flexibility Facility Design

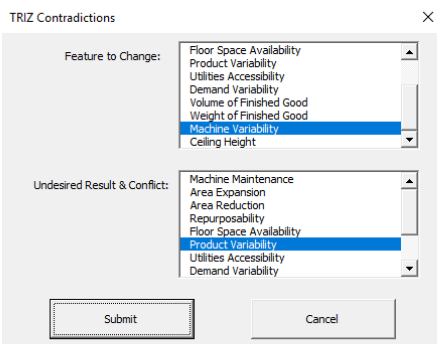
Step 1 of the conflict resolution process is visualized in Figure 4, when the user chooses two desired characteristics for facility flexibility. In this example, they choose parameter A as “Machine Variability” and parameter B as “Product

Variability.” Steps 2 and 3 are shown in Figure 5. For example, the desired building flexibility characteristics of being able to handle both machine variability and product variability returns five principles, including #15 Dynamics, which might include moveable partitions, as shown in Figure 6, and an example of a solution recommended by Gonzalez [21]. After the Excel tool returns the solution space genres and examples, the user selects which principle(s) to use as a starting point for generating innovative solutions to the problem at hand.

The tool follows the general problem-solving model of identifying a specific problem, reducing it to a standard problem model (i.e., the contradiction: improve A without harming B), identifying a standard solution model space (i.e., the inventive principle), and then engineering a final solution [3]. It follows the recommendation of reframing the contradiction matrix with respect to the field [19]. Its development was also consistent with processes observed in TRIZ applications for software design, business and management, and other industries; essentially, it is the creation of a new matrix tool specifically tailored to the language and context of the construction industry.

	Construction Parameter Name	Definition	Example
A	Machine Variability	The ability to have varied machines and equipment within a facility and continuously vary the current machine options	Production of different valves sizes requires the storage of additional dies and unique machinery. Consider using "plug-and-play" pre-assembled movable casework and equipment.
	Plant Site Integration	The ability to integrate the different aspects of the facility (logistics, storage, manufacturing, location, etc.)	As a facility is being constructed, flexibility may be needed for all aspects of production integration. For example, this could involve movable walls, conveyors, and storage locations.
B	Product Variability	The ability to vary the product being produced: either new products or within product families	Consider multi-product capacity impact on facility design. For example, switching between the production of control valves and pressure regulators consists of different layout design requirements.

Figure 4. Step 1 - User Chooses Two Parameters (Contradiction Pair) To Retrieve Relevant Innovative Principles



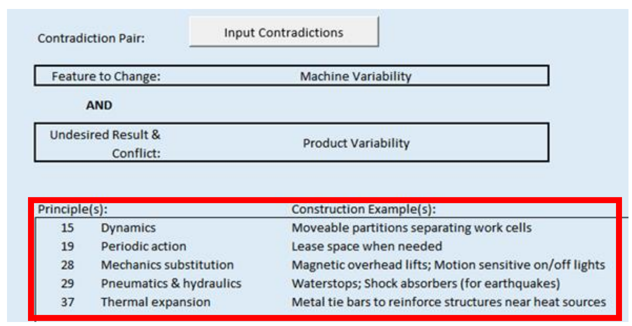


Figure 5. Left: Step 2 - Desired Flexibility Characteristics Are Input As Parameters Into Excel Macro Tool
Right: Step 3 - Inventive Principles Are Identified From Required Parameters For Design Consideration

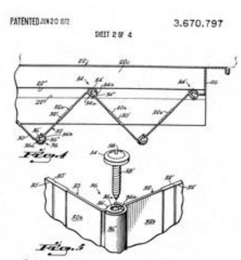


Figure 6: Example of Movable Partition Patent [22], Retrieved by Corresponding Construction Principle

In its current stage, the modified tool is a complete beta level prototype for incorporating TRIZ into the construction industry using the contradiction matrix. Next steps will include partnering with industry users to deploy it to develop case studies while further refining the tool’s construction-specific vocabulary, as different professions have different working vocabularies (construction engineer vs. builder vs. industrial engineer vs. client, etc.). The team expects that immediate reactions for some people new to the tool could be dismissal of some of the parameters and/or principles because of a lack of familiarity with TRIZ. Therefore, tool dissemination will require sufficient instruction about TRIZ to help users understand that unfamiliarity with an innovative solution space in a given context doesn't mean it should be dismissed without consideration; it might be the new, innovative way of solving a problem that hasn't yet been discovered. Another enhancement will include dividing principles that are returned for each contradiction into "conventional" and "alternative" groups. The "conventional" principles will include techniques that construction industry professionals have most likely used or seen previously, such as telescoping, accordion walls, and modular buildings. The "alternative" group will include principles that might not point to obvious solutions but are still worth considering for unique and innovative ways of solving problems. In its dissemination, the potential to use it as a repository to store and to systematically retrieve innovative facility flexibility solutions (designs and relevant technical enablers) will be discussed.

4. Conclusions

Similar to Mann and Catháin's [19] observation about architecture, and Renev and Chechurin's conclusion that the TRIZ contradiction matrix should be adapted to construction engineering and management through case studies [12], the time is right to extend the application of TRIZ into the construction industry. Industrial and construction engineers have recognized the need for and benefits of reduced design time for flexible manufacturing facilities. As Zhang, et al. identified [3], the biggest challenge is to translate generic TRIZ parameters and principles into construction-specific terminology that will encourage professionals to embrace the significance of a new tool for identifying innovative design space while avoiding constraining the brainstorming process. The tool developed is dynamic; it will continue to be revised and improved as better terminology and examples are identified. Next steps include working with industry professionals who can use the tool, and then soliciting and incorporating their feedback.

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