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A self-evolutionary model for automated innovation of construction technologies

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ABSTRACT

Previous approaches for innovation of construction technologies are constrained by the existing processes or engineer's experience and knowledge, thus are essentially incremental. This paper presents a self-evolutionary approach to assist automated innovation of construction technologies. The proposed approach integrates a text mining technique, patent analysis, and a Genetic Algorithm (GA) to form a prototype automated radical technology innovation model that has not been developed before. Previous technology information stored in the public technological repositories (e.g., published specifications, public patent databases, etc.) is adopted as the design knowledge for building the function model of a target technology. It is then translated into a genetic operation tree (GOT) for the self-guided evolution with a GA. Finally, the innovative solution is recovered as a function model and realized in a 3D model. A traditional road manhole construction technology is selected as demonstration case study to show the feasibility and potentials of the proposed method for automated innovation of construction technologies.

1. Introduction

Creative economy has been identified as the major driving force for the next wave of world's economic growth [5,8]. It is especially meaningful to the current challenges of global change to the construction industry [29]. No matter the challenges are due to the extreme weather effects or over-urbanization, they have never been confronted and dealt with by the human beings before. Robert Harris pointed out that the Construction Engineering and Management (CEM) academia has overlooked the construction technology research in the past [11]. Shen identified construction technology research as a key approach to meet the future challenges of construction sustainability [29]. Due to the adopted research techniques, mostly related to process-based simulations [9] or classical constructability improvement methods [35], the technology innovation of the previous research was relatively limited and incremental [43].

Just recently, patent analysis and the theory of inventive problem-solving (TRIZ) were adopted in the innovation of construction technologies [21,22,27]. Such methods escape from the existing processes-based approach and generate innovative solutions based on global human intelligence (mainly from the public patent databases), thus result in automated and radical innovations that may bring in significant benefits for human beings [43].

The paper presents preliminary results of a research project on developing a Model for Automated Generation of Innovative Alternatives (MAGIA) that integrates the most advanced computer-aided innovation (CAI) techniques and a specialized genetic algorithm (namely genetic operation tree, GOT) to form a prototype automated radical innovation model for construction technologies.

The proposed MAGIA intends to lower the uncertainties involved by human judgments (and thus resulted in local optimum) and reduce the manual efforts required for processing huge amount of technological information during innovation process. A specialized technology modeling technique and a self-guided model optimization algorithm are adopted to automate the alternative generation of technology innovation process. A prototype system is developed to implement and test the proposed MAGIA. A real world example of traditional road manhole construction technology is selected as case study to demonstrate the feasibility and potentials of the proposed method. Issues regarding to the implications to future construction challenges, the assumptions, and the limitations of the proposed model are addressed and discussed.

2. State of the art in construction innovation

Innovation of construction technologies has resulted in dramatic revolutions in construction practice. For example, the introduction of Portland cement in 1824 has brought up thousands of new construction technologies and equipment that completely change the way of construction engineering. In the first quarter of the 20th century, the steel structural technology was invented and introduced to construction industry, which triggered a second wave of revolution

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for construction technologies. During the late 1970s, the construction industry suffered in low productivity, hence inspired the next generation of construction innovation. Issues such as constructability [25], prefabrication, modularization [35], and automation [31] have drawn numerous researchers to devote in the innovation of construction and management processes.

In spite of the tremendous efforts spent, innovation in construction industry has been relatively slow [39]. Lack of a common framework, as pointed out by Halpin [10], may be blamed for this lag. Previous researchers have exploited different approaches for organization process innovation [34], technology evaluation [42], and advanced technology repositories [13]. However, few of these efforts target were directly related to design of new technologies. Halpin proposed a CYCLONE model for analysis and improvement of construction processes [9]. Many efforts on construction process simulation followed him, e.g., COOPS [19], STROBOSCOPE [23], etc. Most process simulation techniques are still limited to the modeling of existing processes, rather than the invention of new processes or technologies.

Just recently, a new area of construction innovation has been developing on patent analysis (PA) [27] and the Theory of Innovative Problem Solving (TRIZ) [21,22,36]. The former innovates the target technology based on existing technologies of the other areas, which are stored in public patent databases; the latter applies a systematic procedure to identify potentially improvable engineering contradictions with tools provided by TRIZ [2].

Unlike the simulation-based approach that innovates on the existing construction processes, the PA- and TRIZ-based technology innovation methods seek a different dimension of technology improvement by introducing technological information from outside of construction domain. The former belongs to “incremental innovation”, and the latter belongs to “system innovation” or “radical innovation” according to the classification of Sarah Slaughter [30]. Although the PA- and TRIZ-based methods open a new window for radical innovation of construction technologies, they still suffer in requirement of heavy human involvement during the alternative generation in the innovation process. Such requirements do not only hinder the adoption of those methods but also form a bottleneck of technology innovation.

3. Function modeling for construction technologies

Before an automated technology innovation model is developed, it is required to define a “common language”, as appealed by Halpin [10], for describing the characteristics of a target technology. For this end, the technology characteristics should be translated into a model that is operational for computer-aided innovation. This section describes a relevant model widely adopted in mechanical and product design, namely function model (FM) [26], from the viewpoint of construction technologies.

3.1. Vocabulary of function modeling

Functional modeling is a critical method and the key step in a product design process [32]. It has been widely adopted in mechanical and many other areas and has demonstrated its benefits for assisting product designers [16,26,32]. There have been numerous functional modeling methodologies proposed by different researchers ([16,26,38,44–46]). All of which follow a similar procedure: they begin with an overall product function and then break that function down into sub-functions via a process similar to the Work Breakdown Structure (WBS) method that is widely adopted in construction project management.

The early efforts on function modeling research traced back to the value analysis of a product [1,20]. In value analysis, the functions of a product are defined in terms of a verb plus a noun (V + N). A list of verb-noun functions was suggested to represent the common functions associated with a product. The functional modeling method proposed by Pahl and Beitz [26] may be the most well-known. A schematic representation of the basic FM based on Pahl and Beitz's methodology is shown in Fig. 1. They model the overall *function* of a product and decompose it into *sub-functions* operating on three types of *flows*: energy, material, and signals.

Their function modeling approach was a great advance in engineering design, but their methodology did not provide a comprehensive list of sub-functions to describe all possible engineering systems or produce repeatable functions [15]. Two engineers may generate two different function models for a set of same product/technology and customer needs. Many researchers have tried to improve the weakness of Pahl and Beitz's methodology by developing a common vocabulary for functional modeling [15,16,32,38]. A summary of the common vocabulary for the functions and flows is shown in Tables 1 and 2, respectively.

3.2. Subject–action–object function models

In addition to the Pahl and Beitz's FM and their families, another popular FM that is widely adopted by commercial computer-aided innovation (CAI) software (e.g., Goldfire Innovator®, CREAX®, etc.) is the Subject–Action–Object (SAO) function models. The SAO FM in systems engineering and software engineering is a structured representation of functions, activities or processes within the modeled system or subject area [24]. A SAO FM defines the relationships between system elements in terms of the functions they perform [18]. In a SAO FM, a *function* is an “*action*” that directly changes or maintains a controllable or measurable **parameter** of a (material) *object*." The SAO FM is depicted in Fig. 2. Examples of *actions* are move, remove, burn, weld, count, deposit, inform, rotate, hold, conduct, carry…, etc. The SAO FMs represent a system (describing the functions of a product/technology) with two natural language templates: (1) Action–Object (AO), e.g., move (A) table (O); (2) Subject–Action–Object (SAO), e.g., conveyer (S) moves (A) table (O). A **parameter** is a directly measurable or controllable characteristic associated with a material *object* which is affected by a function. Examples of parameters affected by *actions* are length, area, volume, mass, density, volts, bits, joules, coulombs, temperature, roentgens…, etc. A common way to identify the SAO FM for a product/technology is by asking the following questions: (1) What **parameter** of the *object* is controlled of changed by the ***action***? (2) How do I measure *action object*?

Comparing the Pahl and Beitz's FM with the SAO FM, it is identifiable that the black box *function* of Fig. 1 (defined in Table 2) comprises *Subject* and *Action* of Fig. 2; the *flow* of Fig. 1 (described in Table 1) is relevant to the *Object* and the associated **controllable parameter** of Fig. 2. As a result, a Pahl and Beitz's FM can be exactly transformed into an SAO FM. Besides, the SAO FM is more relevant to the V + N function definition in value analysis [20]. It is also more intuitive to the construction engineers who are familiar with the value analysis. As a result, the SAO FM is adopted to model a construction technology hereafter in this paper.

3.3. Process of FM generation

The SAO FM provides a useful tool to capture the functional characteristics of a construction technology. In this sub-section, a generic process for generating function models is introduced. Kurfman et al. [15] proposed a five-step generic procedure for deriving the FM of a product/technology: (1) identify flows that address customer needs—identify the flows (the physical phenomena) that the

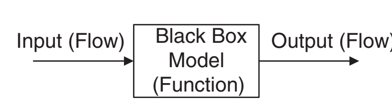

Fig. 1. Schematic representation of Pahl and Beitz's FM.