Designing Flexible Engineering System Using a Sensitivity-based Method

Junfei Hu, Kim-Leng Poh

Abstract—Engineering systems are continuously changing in order to adapt to dynamic environment. Adding flexibility in engineering system design can reduce risks arising from uncertainties. This paper presents a method to identify flexible system design opportunities under uncertainties. The method focuses on the flexible design opportunities at the initial design phase of engineering system. It analyzes both direct and indirect relationships from exogenous factors to system design variables. An exogenous factor searching algorithm is proposed to quantitatively and efficiently measure the sensitivity of each design variable, given a complex inter-relationship of a system. The design variables, which are the most sensitive to the exogenous factors, are introduced with the flexible design opportunities. The proposed method is applied in a case study on transportation system design. It shows that adding flexibilities into the selected opportunities results in significant reduction in the total cost of the project over long term period.

***Index Terms*—Flexible design opportunities, sensitivity, external uncertainty**

I. INTRODUCTION

Engineering system design becomes increasingly complex and challenging with the emerging of new technological opportunities and changing environment. The traditional methods for engineering system design often focus on optimizing system's performance based on an assumption that the external environment is deterministic. Generally, the uncertainties are not recognized and considered in the engineering design process. Therefore, the traditional methods can lead to an optimal solution only if the future is relatively stable. However, most of the engineering systems are set up for long term use and the environment cannot keep in certain during the long term lifecycle in practice. For example, the factors, such as the regulations and technologies, may be changed, during the lifecycle of engineering system. Those exogenous factors may affect system's value and performance. In such a situation, the traditional methods without taking into account uncertainties often result in suboptimal design choices.

In order to deal with uncertainty in system design, flexibility has become an increasingly important design criterion in the system design process for engineering systems [1]. Many applications, such as water resource systems [2], offshore oil platforms [3], [4], infrastructure systems [5], [6] etc., have shown that system design with flexible design opportunities can increase the overall performance, compared to traditional design process. Therefore, it is not surprising that flexible designs are widely used in many real world applications.

According to [2], [7], flexibility can be considered in two ways: "on" system and "in" system. Flexibility "on" system is related to management decisions. It affects system as a whole component. For example, the flexibility to abandon and expand a project between two decision phases is the source of flexibility "on" system. Flexibility "on" system can be easily incorporated in design. Furthermore, the valuation of flexibility "on" system has been well investigated in the literature, including methods based on real option analysis. Flexibility "in" system design, on the other hand, refers to the ease with which changes can be made within a system due to the influence of external factors of system. Its goal is to make a system adaptable to its environment by incorporating flexibilities within the physical components of system. Recent research on flexibility "in" system has mainly focused on valuation of flexible options based on the assumption that the flexible design opportunities are available a priori (e.g., [8]). However, the identification of flexible design opportunities is also a vital aspect in the system design, since it ensures that all flexible design alternatives are investigated during the design process. In the existing literature, the research on the identification of flexible design opportunities is still limited.

In this paper, our research focuses on the area of flexibility "in" system. Specifically, we are interested in the problem of identifying where flexibilities should be embedded in engineering system design. A sensitivity-based method for identifying flexible design opportunities is proposed. The proposed method identifies flexible design opportunities based on whether the design variables are sensitive to the external uncertainties or not. In other words, if the design variable is either directly or indirectly influenced by the exogenous factors, it will be considered as a potential flexible design opportunity in the design process. In order to find the entire influence paths from exogenous factors to design variables, an exogenous factor searching algorithm and a flexible opportunity selection algorithm are presented. It quantitatively measures the sensitivity of each design variable for engineering system design.

Our work is inspired by some previous work; however, it differs from existing methods in several aspects. First of all, our work uses the directed graph to represent the

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inter-relationships among exogenous factors and design variables in the engineering system. This allows designers to analyze the system in a systematical manner. Secondly, our work identifies both direct and indirect influences from external uncertainties to design variables. Third, it quantitatively measures the sensitivity of design variables. This helps designers to identify which are the most sensitive design variables to exogenous factors. The designers can focus on this set of variables when designing flexible alternatives. This work was partially published in [9]; here is an extension of it.

The remainder of the paper is organized as follows. Section 2 discusses the existing works of identifying flexible design opportunities. Section 3 defines the concept of sensitivity and the quantitative measurement of sensitivity. Section 4 presents the procedure of sensitivity-based method. Section 5 shows a case study based on the design of a hypothetical High Speed Rail (HSR) system. Section 6 concludes with a summary and suggests future work.

II. RELATED WORK

Recently, several methods have been developed to address the problem on identifying where flexibility to embed in design process. The existing work can be organized into two categories: the Design System Matrix (DSM)-based method and the screening methods. The Design System Matrix (DSM) is a compact and visual representation of complex system. It supports system decomposition and integration problems. The nodes in DSM represent the parameters within the system and the marks inside the matrix represent the relationship (the detail is illustrated in [10]). Many existing methods use DSM as the basis of system model.

The change propagation analysis (CPA) is one of the DSM-based methods. It uses DSM matrix to measure how changes in design components propagate through a system [11]. According to [11], the components which propagate more changes to other design components than they received, called multiplier, are prime candidates for incorporating flexibility in an engineering system. The CPA is useful when only one external change is imposed on the system.

Another representative method is sensitivity Design Structure Matrix (sDSM). It is used to develop platform design process is another representative method [12]. The sDSM method looks for the design variables which are insensitive to the changes of design variables and functional requirements. The Invariant Design Rules (IDR) algorithm is presented accordingly to identify the potential platform components. Once the platform components are identified, designers can limit their effort to further evaluate these components. The sDSM is suitable when the direct relationships are easily identified in early design phase. The Engineering System Matrix (ESM) is extended from CPA and sDSM by not only considering the uncertainties from technical environment, but also taking into account the uncertainties from human and social environment[13].

The benefit of DSM-based methods is that all system components are considered in early design process and potential design opportunities where the flexibility can embed in will not easily be omitted in the identification process. However, they still have some limitations. First of all, the DSM-based methods are used to construct the optimal platform design. However, how to identify the flexible design opportunities in the system engineering design is not clear. Secondly, in most DSM-based methods, only the direct relationships are considered. For example, in the CPA method, the change propagation index of a particular element is measured by comparing the direct change “in” the element and the direct change “out” the element. Another example is sDSM, the insensitive platform component is selected only when there are no direct relationships from functional requirements and other design variables to it. However, in the real world, a simple change to one part will propagate though a system and result in changes to a series of others since the system design are connected. For example, if part A is changed, part B needs to be changed to facilitate this perturbation. Meanwhile, a change to part B also leads to a change in part C. If we only consider change of part B and ignore the change propagation (i.e., potential change of part C), it might result in suboptimal solution. Therefore, only considering the direct relationship is not suitable in the real world analysis.

Currently, how to predict change propagation is an interesting problem faced by many researchers. The change prediction method (CPM) is also one of the DSM-based methods which predict the risk of change propagation in complex systems [14]. The likelihood of the change occurring and the impact of the subsequent change are considered in the CPM method. It predicts the likely change propagation paths and their impact on a system by exploring the connectivity of each component within the system domain. The CPM provides the knowledge to allow changes which are easier to implement, as well as avoid changes which have more impacts to whole system in the redesign phase. However, how to predict change in the initial design phase and how to identify flexible design opportunities is not clear.

Another category of the existing work is screening methods. The screening methods are widely used to explore the design space to find valuable system configurations. The optimization screening method is proposed by Wang [2]. It is used to design a river dam for hydroelectric power production in China. The representative exogenous scenario is prior information, which is assumed to be identified before modeling. Each exogenous scenario can find an optimal design configuration. The design variables that are altered from one optimal design to another design show good opportunities to embed flexibility. This method can find the optimal solutions for system design. However, it is difficult to find representative exogenous scenarios before modeling. In addition, computational resource is another problem when finding the optimal solution for large-scale engineering systems. In order to save the computational resource, different type of search algorithms are proposed. One of the representative works is suggested by Cardin [15]. The adaptive One-Factor-At-a-Time (OFAT) algorithm is presented to explore the design space. Although the OFAT algorithm can speed up the design exploration process, it is an approximate method and cannot guarantee to find the optimal solution.

The previous works discussed above have been widely used in many applications for identifying the flexible design opportunities. In order to identify flexible design opportunities of engineering system, which has large number of design variables and complex relationships, a sensitivity-based method is presented in this paper. Specifically, our work is an extension of DSM-based method; however, it distinguishes from DSM-based methods in several aspects. In addition, our work focuses on the engineering system design by using the directed graph. It provides good representation of the system and interconnections between components, which allows the designers to analyze the system insightfully. In addition, our work is not only considering the direct relationships, but also considering the indirect relationships, which can address some challenges discussed above.

III. PRELIMINARIES

The sensitivity-based method is aimed to find the system's design variables which are sensitive to exogenous factors. Specifically, it attempts to find the system's design variables that need to be changed in order to adapt to the changes of exogenous factors. Those design variables which are identified by the sensitivity-based method are defined as flexible design opportunity in this paper. Identification of flexible design opportunities allows flexibility incorporation in the early phase of the design process. It makes the system adaptable to its changing environment and provides a good performance in long time horizon. In the next section, we will first formally define the concepts of sensitivity and the quantitative measurement of sensitivity.

A. *Concept of sensitivity*

Directed graph is used to present the complex relationships between design variables and exogenous factors in the sensitivity-based method. Fig 1 shows a graph representation of a generic engineering system. Nodes x represent design variables, which are within the system boundary. Exogenous factors, which are presented by nodes ef in Fig 1, account for external uncertainties. The directed arcs in Fig 1 represent the direct influence relationships. For example, the arc between exogenous factor ef_m and design variable x_3 means that when the exogenous factor ef_m changes, the design variable x_3 needs to be changed accordingly.

In reality, the design variables are not only directly influenced by exogenous factors, but also indirectly influenced by exogenous factors through other design variables. For example, in Fig 1, the design variable x_3 is directly influenced by exogenous factor ef_m. Similarly, the design variable x_3 may be indirectly influenced by the exogenous factor ef_3 though the design variable x_2. This is represented by a path from the exogenous factor ef_3 to the design variable x_3 in Fig 1. This indirect influence means that any change of the exogenous factor ef_3 may instigate the change of design variable x_3 through the perturbation of the design variable x_2. Although indirect influence relationship and direct influence relationship affect engineering system in different ways, both of these relationships are important for the designers. This is because that both of the relationships can instigate the changes of design variables. Therefore, the design variable is sensitive to the exogenous factors by direct or indirect influence relationship.

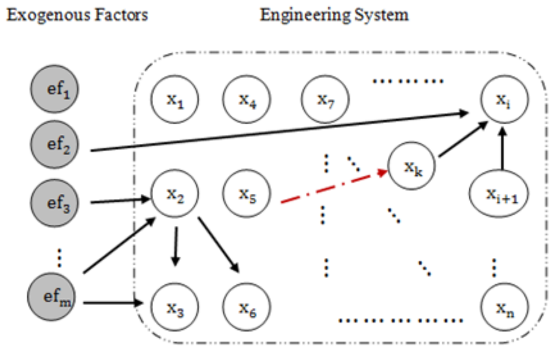

Fig 1: Engineering system with complex relationships

The sensitivity of design variable can be expressed mathematically. Consider a system which can be described using n design variables $X=\{x_1, x_2, \cdots\cdots x_n\}$. Meanwhile, exogenous factor of the system is analyzed, according to future uncertainties, the exogenous factor set is $EF=\{ef_1, ef_2 \cdots\cdots ef_m\}$. Let G be a directed graph, $G=(V, E)$ representing the system, where $V=X \cup EF$. If $(v_i, v_j) \in E$, where $1 \le i \le (n+m), 1 \le j \le (n+m), i \ne j$, we say that there is an arc from v_i to v_j. The node v_i is parent of node v_j. This arc also means that if a unit change Δv_i occurs, the variable v_j will need to change to facilitate this perturbation in v_i. Therefore:

$$[(v_i, v_j) \in E\ ] \supset [(\Delta v_i \ne 0) \supset (\Delta v_j \ne 0)] \tag{1}$$

Definition 1: If $(\Delta v_i \ne 0)$, then $(\Delta v_j \ne 0)$. The node v_j is *sensitive* to the node v_i in this situation.

Let D_{ef_k} be the set that contains all the descendent node of ef_k, $k=1, 2, \cdots\cdots m$. D_{ef_k} is a subset of X. The descendent of k^{th} exogenous factor is denoted as x_p^k, where $1 \le p \le n$, $x_p^k \in D_{ef_k}$.

Definition 2: the node $x_q \in X, 1 \le q \le n$, is *sensitive* to the exogenous factor ef_k if and only if $(ef_k, x_q) \in E$ or $\exists x_p^k \in D_{ef_k}, (x_p^k, x_q) \in E, p \ne q$. Therefore,

$$[(\Delta \mathrm{ef_k} \ne 0) \supset (\Delta \mathrm{x_q} \ne 0)]$$

$$\equiv \{[(\mathrm{ef_k}, x_q) \in E\ ] \vee \{[(\exists x_p^k, x_q) \in E] \& (p \ne q)\}\} \tag{2}$$

We define the sensitivity of each design variable in a graphical manner. A design variable is said to be *sensitive* in the neighborhood of a particular exogenous factor under any of the following two situations:

1) *Direct influence* The design variable is directly influenced by an exogenous factor. In other words, there is an arc from the exogenous factor to the design variable in the directed graph (e.g. $ef_m - x_3$);
2) *Indirect influence* The design variable is indirectly influenced by exogenous factors through another design variable. In other words, there is a path from the exogenous factor to the design variable in the directed graph (e.g. $ef_3 - x_2 - x_3$).

B. *Quantitative measurement of sensitivity*

The concept of sensitivity is defined as direct/indirect influence from exogenous factor to design variable. In this subsection, we will define the measurement of sensitivity for each variable.

Let EF_q^* be a subset of EF which contains all the exogenous factors that have direct or indirect influence to design variable x_q . It is defined as follows:

$$EF_q^* = \{ef_k | (\Delta ef_k \neq 0) \supset (\Delta x_q \neq 0), \forall\, ef_k \in EF\} \quad (3)$$

The variable C_q counts the number of variables in set EF_q^*. The sensitivity of variable x_q is denoted as S_q.

Definition 3: a design variable $x_q$as being *more sensitive*, compared to another design variable x_p , when x_q is influenced by more exogenous factors compared to x_p. It can be described as follows:

$$(C_q > C_p) \supset (S_q > S_p), \quad 1 \leq \text{p} \neq \text{q} \leq n \quad (4)$$

For example, in Fig 1, there are two paths from factors ef_3 and ef_m to variable x_6 . Therefore, the variable x_6 is sensitive in the neighborhood of factors ef_3 and ef_m. Now, for variable x_3 there are three paths from exogenous factors ef_3 and ef_m to variable x_3 . However, the sensitivity of variable x_3 is the same with variable x_6 because variable x_3 is only sensitive in the neighborhood of the two factors ef_3 and ef_m . Therefore, in the sensitivity-based method, the sensitivity of each design variables can be measured by the number of exogenous factors which can affect it. It is not measured by the number of paths from the exogenous factors to a particular design variable.

IV. SENSITIVITY-BASED METHOD

In the previous section, the sensitivity of design variable is defined and quantitatively measured by counting the number of influencing exogenous factors. The influence path from the exogenous factors to the design variables can be easily identified when a system has simple inter-relationships among design variables. However, in most real-world applications, a large number of design variables are usually required and the interconnections among the design variables are usually complex. For example, the sensitivity of the design variables cannot be identified easily when the system as shown in Fig 1 is designed. Specifically, the relationship path from factor ef_m to variable x_i is difficult to find. A sensitivity-based method is presented in this section to efficiently find the entire paths from the exogenous factors to a particular design variable and finally identify flexible design opportunities for designers in the early design phase. The detail of sensitivity-based method is described in this subsection.

A. Overview

Fig 2 describes the procedure of the sensitivity-based method. This method assumes that external uncertainties can be analyzed in the early design phase. The directed graph can be constructed after the system design variables and influence relationships are determined. Subsequently, reverse the arcs in order to efficiently search paths. Thirdly, search the influence path from particular design variables to exogenous factors using exogenous factor searching algorithm. The sensitivity of the particular design variable will be increased when there is a path from the design variable to exogenous factor. The sensitivity of each design variable is measured by the number of exogenous factors which have influence path to it. This algorithm quantitatively and efficiently calculates the sensitivity of design variables. The flexible design opportunities are finally identified by flexible opportunity selection algorithm which compares sensitivity of each design variable. The optimal flexible design opportunity is the design variable which is most sensitivity to external uncertainty.

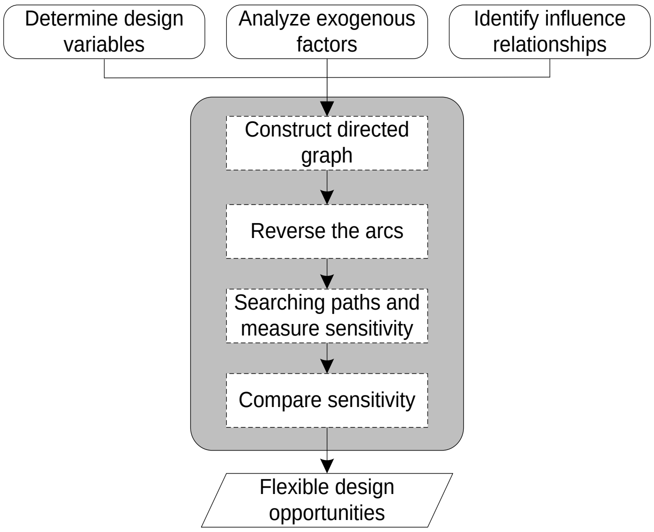

Fig 2: The procedure of sensitivity-based method

B. Construction of the directed graph

The construction of directed graph is an important preparation work. In order to ensure the accuracy and integrity of the analysis, designers need to capture design variables, analyze exogenous factors and identify influence relationship as comprehensively as possible. However, in the real design process, it is difficult to construct the directed graph in detail since designers can rarely acquire the whole knowledge about highly break down system. In addition, such detail analysis is tedious and time-consuming. Therefore, in this research, we focus on the component level analysis. It means that we just break down the system into subsystems rather than parameters. We can limit our resources to analysis parameters after we identify flexible design component.

There are two types of influence arc to represent change influence being considered during the construction process: the arcs from exogenous factors to design variables and the arcs between design variables. However, only the change influences which change instigate agent is external to the system are considered during the construction process. It should be noted that when construct the directed graph *G*, no arcs should be included from design variable to exogenous factor. This is because that we do not consider the influence of design variable to exogenous factors.

C. Reverse arcs for graph G

The proposed method is based on depth-first search (DFS) algorithm. DFS is one of the techniques for traversing a graph. It starts at the root and explores as far as possible along each branch before backtracking [16]. Specifically, in this system engineering domain, the algorithm starts at a design variable called *n* and visits the first child node of *n* in the graph and goes deeper and deeper until a factor node *f* is found or until it hits a node that has no children. Then the search backtracks, returning to the most recent node which has not been visited. If a factor node *f* is found, it shows that there is a path from factor node *f* to variable node *n*, and therefore the factor node *f* can affect the variable node *n*. The sensitivity of the variable node *n* will be incremented by one. After traversing a graph, all factor nodes, which can affect the design variable *n* will be found.

The DFS algorithm starts at the root node and then traverses the whole graph. Given the directed graph *G*, (example in Fig 3 (a)), if we need to measure x_2's sensitivity, the algorithm will start at exogenous factors (e.g., ef_1, ef_2 and ef_3) sequentially. Therefore, it traverses the graph three times in order to find whether there is a path from ef_1, ef_2 and ef_3 to node x_2. Although it can measure the sensitivity in this way, it is not an efficient way when there is a large number of design variables and exogenous factors. In order to quickly find the sensitivity of a design variable, the directions of the arcs in the directed graph *G* are reversed in the proposed algorithm. The corresponding graph *G'* is showed in Fig 3(b). In this case, the root nodes are now design variables. The sensitivity-based method can then start at node x_2 and traverse the graph only once to find those paths from exogenous factors ef_1, ef_2 and ef_3 to node x_2.

D. *Exogenous factor searching*

In this subsection, we will introduce the exogenous factor searching algorithm to search influence paths from design variables to exogenous factors. The algorithm involves three inputs: 1) the graph with reversed arcs *G'*, 2) set of all design variables, and 3) set of all exogenous factors. The algorithm traverses the graph in a depth-first fashion and measure the sensitivity by counting the exogenous factors.

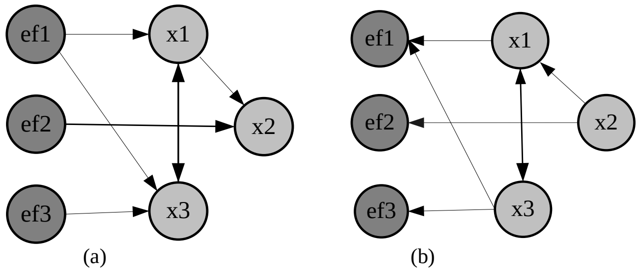

Fig 3: (a) The directed graph *G*; (b) The reversed graph *G'*

In the algorithm 1, the loop starting on line 2 ensures that all design variables are visited. The *for* loop on line 4 marks all the variables as unvisited firstly. The algorithm starts from one of the nodes in the variables list. The *while* loop on line 6 traverses all child variables in both variable list and exogenous list. Inside this loop and between the lines 9 and 11, the sensitivity of a node is increased when a factor node is visited. After traverse the whole graph, all exogenous factors which directly or indirectly connect with the variable node are identified. Thus, by the end of *for* loop (line 16), the sensitivities of all variables can be identified. The flow chart of exogenous factor searching algorithm is described in Fig 4.

Algorithm 1: Exogenous factor searching

```
Procedure:
1: G' = reverse arc's direction of G
2: for each node n in variable list do
3:     Stack S = {}  // start with an empty stack
4:     for each node u in G', set u as unvisited
5:     push S, n
6:     while (S is not empty )do
7:         u = pop S
8:         if (u is not unvisited in G'), set u as visited
9:             if (u is a node in factor list) then
10:                increase sensitivity value of n
11:            end if
12:            for each unvisited neighbor w of u in G' do
13:                push S, w
14:            end for
15:    end while
16: end for
```

E. *Flexible opportunity selection*

After the sensitivities of all variables are identified, the optimal flexible design opportunities need to be selected. The flexible opportunity selection algorithm compares the sensitivities of all variables and finally selects the most sensitive variable. The input of this algorithm is *the sensitivity value of each design variable* which can be obtained by exogenous factor searching algorithm. It stars from *for* loop (line 2) to make sure that the entire design variable can be compared. By the end of *for* loop (line 9), the sensitivity list contains the most sensitive variables. The variables which are selected in the sensitivity list are the potential opportunities where flexibilities can be added in future design process.

Algorithm 2: Flexible opportunities selection

```
1:  max sensitivity = 0
2:  for each node n in variable list do
3:      if sensitivity value of n > max sensitivity then
4:          max sensitivity = sensitivity value of n
5:          clear sensitivity list and add n into the list
6:      else if sensitivity value of n == max sensitivity
7:          add n into sensitivity list
8:      end if
9:  end for
10: return sensitivity list
```

V. CASE STUDY

High Speed Rail (HSR) system allows trains to operate at speeds over 200 kph (125 mph) and becomes one of the popular transportation systems nowadays. At present, it regularly operates in Japan, France, Germany, and other countries worldwide. In this section, a case study on the design of a hypothetical HSR system is presented to illustrate how to use the sensitivity-based method to effectively identify flexible design opportunities. The optimal flexible design opportunity is selected by comparing the sensitivity which is quantitatively measured by exogenous factor searching algorithm and flexible opportunity selection algorithm. The optimal flexible design alternatives are analyzed and finally compared with traditional deterministic design.

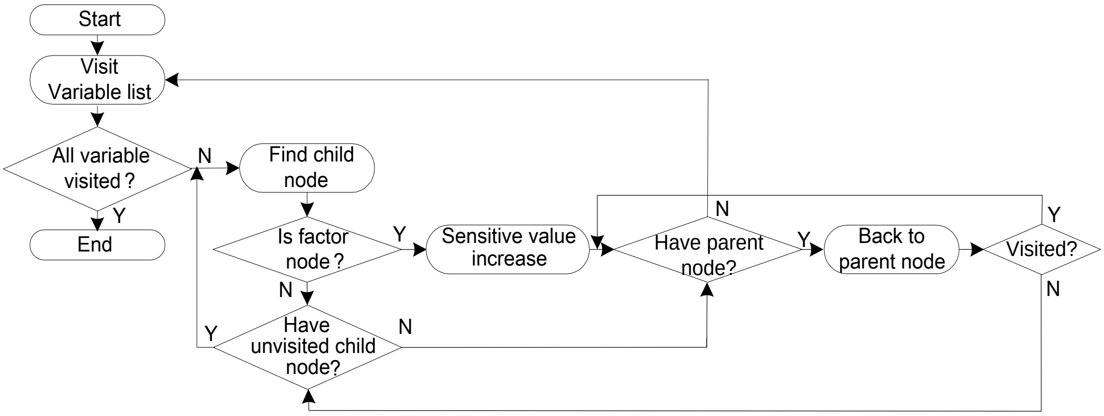

Fig 4: The flow chart of exogenous factor searching algorithm

A. Identify exogenous factors and design variables

There are a number of characteristics that should be used in evaluating HSR systems. According to [17], these include travel demand, schedule performance, ride quality, noises, safety, energy conversion efficiency, actual travel time, reliability and so on. These factors are external to the HSR system, and they are the main sources of uncertainty to the HSR system. In this case study, five critical exogenous factors are selected. They are travel demand, ride quality, actual travel time, arrive on time rate, and energy conversion efficiency, as defined in Table 1. All of these exogenous factors are the sources of uncertainty because of the competition from air market and bus vehicle market, or technical innovation. The criteria of these exogenous factors are uncertain during the life cycle of HSR system.

Table 1: Exogenous factors in the hypothetical HSR system

Exogenous Factors	*Description*
Travel demand	Predicted number of passengers in one year. It is growing as population expands in a particular region
Ride quality	Comfortability of passenger's travel experience
Actual travel time	The travel time for passenger between origin and destination
Arrive on time rate	Ratio between the number of on time arrival train and total arrival train.
Energy conversion efficiency	System design efficiency with respect to energy consumption

The HRS system is divided into three subsystems. They are station subsystem, vehicle subsystem and track subsystem. The design variables are identified according to [17]-[20], which are showed in Table 2.

All of the relationships among exogenous factors and design variables are identified based on [17]. For example, the actual travel time is one of the exogenous factors. It is affected by several variables. They are 1) train's ability to negotiate curves; 2) train's ability to accelerate and decelerate quickly; 3) number of station stops and dwell time at each station. Specifically, if passengers require shorter travel time, some variables within HRS system need to change, such as operating speed of the train, accelerate system, brake system, dwell time and number of station. The inter-relationships among design variables and exogenous factors in our hypothetical HRS system are represented using a direct graph, as showed in Fig 5.

Table 2: Design variables in the hypothetical HSR system

Subsystems	*Design Variables*
Station system	Span of service, waiting space on station, number of stations, frequency, arrangement of moving rout, in-station facilities, dwell time at each station
Vehicle system	Configuration of train, seating capacity, accelerate system, brake system, control system, track-train interactions, personal space on train, traction system, operating speed, gearing system, total weight, communication system, aerodynamic system, propulsion system
Track system	Design speed, signaling system, curvature, catenary, gradient design, superelevation of the track

B. Sensitivity evaluation

In this case study, there are 27 design variables and 5 exogenous factors. Using the sensitivity-based method, 12 design variables have sensitivity value 1, 14 design variables have sensitivity value 2, and 1 design variable has sensitivity value 3. It is found that the design variable of "in-station facilities" is the most sensitive variable in this case. It is influenced by carrying capacity, ride quality and actual travel time directly and indirectly. Therefore, the HRS system will be more nimble in the future when the variable of in-station facilities is designed with flexibility. Next, we will add flexibility into the facilities and compare the flexible system design with deterministic design by the expected total cost.

C. Comparison

After identifying the variable for embedding flexibility identified, the system designer needs to generate flexible design alternatives. Based on the analysis above, we analyze the "in-station facilities" design variable. Specifically, we focus on pedestrian bridge's development in a station. Pedestrian bridge is built to transfer passengers to access the platforms. The number of bridges depends on travel demand in the region and ride quality of passengers. If fewer bridges are developed, the bridges may become too crowded when travel demand increases quickly. Even worse, it may exceed the capacity of the design. In such situation, these bridges

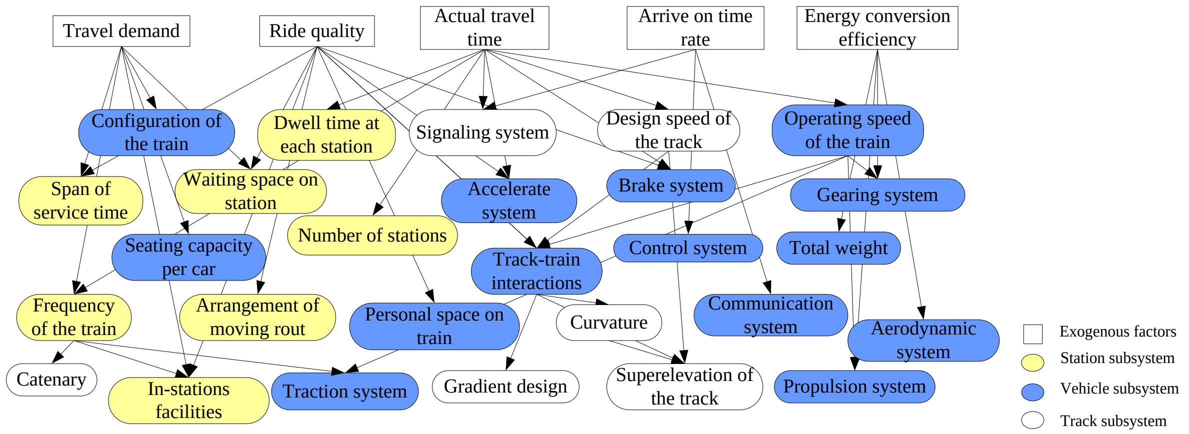

Fig 5: The constructed directed graph of the hypothetical HSR system

require more maintenance cost, compared to regular maintenance cost. In addition, passengers' satisfaction may decrease. On the other hand, if more bridges are developed, extra annual maintenance cost is needed. Therefore, the problem here is to find how to design the pedestrian bridges in order to minimize total cost.

We assume that the deterministic forecast of travel demand in the first year is 7.5 million people, and rises exponentially in the future years. At the end of 30 years, the travel demand will increase to 12.41 million. In the real world, the actual travel demand is uncertain, given the long time horizon. We assume that the uncertainty of future demand is 50%, and the annual volatility for growth is 15%. The designed flow rate of the pedestrian bridge is 5000 people per hour. The peak hour demand is 2.5 times the regular demand. The assumed construction cost and maintenance cost are shown in Table 3. The number shows in Table 3 is relative cost. The extra maintenance cost is required when the actual travel demand exceeds the designed flow rate. The decreased satisfaction from passengers is also represented by cost, which is called satisfaction reduction cost.

Table 3: Construction and maintenance cost per year (×1000)

Category	*Cost*
Initial construction cost per bridge	5000
Maintenance cost for year 1-5	20
Maintenance cost for year 6-20	100
Maintenance cost for year 21-30	200
Extra maintenance cost per person	2
Satisfaction reduction cost per person	1

Based on the above information, three design alternatives are compared in this section:

1) *Deterministic design A* Build one pedestrian bridge in station.
2) *Deterministic design B* Build two pedestrian bridges in station
3) *Flexible design C* Build first pedestrian bridge in station. Meanwhile, design the footings and columns for the second bridge. When the actual travel demand exceeds the designed flow rate of the bridge in two consecutive years, the second bridge will be built. The initial cost for flexible design is 8 million and the construction cost for the second bridge is 4 million. Compared to the deterministic designs, the initial cost for flexible design is increased. However, this is the premium to acquire the real option for future easy update.

The total cost of design alternatives A or B is calculated as follows:

$$TC_{(A\ or\ B)} = C_I + \sum(C_M^i + C_{EM}^i + C_S^i) \qquad (5)$$

$TC_{(A\ or\ B)}$ is the total cost of design A or B, C_I is the initial cost for construct the bridge, C_M^i, C_{EM}^i, and C_S^i are the annual maintenance cost, extra maintenance cost and satisfaction reduction cost at each year *i* respectively. When the actual travel demand for peak hour exceeds the designed flow rate at year *i*, C_{EM}^i and C_S^i are needed. Otherwise, both of these two terms are zero in equation (5). The equation for calculating the total cost of flexible design C is different from equation (5), which shows as follows:

$$TC_C = C_I + C_{NI} + \sum(C_M^i + C_{EM}^i + C_S^i + C_{NM}^i) \qquad (6)$$

where C_{NI} , C_{NM}^i are the initial cost and the maintenance cost for building second bridge respectively, and the meanings of C_I, C_M^i, C_{EM}^i ,and C_S^i are the same as equation (5). When the actual travel demand for peak hour exceeds the designed flow rate of the bridge in two consecutive years, the second bridge will be built. Therefore, C_{NI} and C_{NM}^i are calculated in equation (6). Otherwise, C_{NI} and C_{NM}^i are zero in equation (6). It should be noted that the discount rate for calculating the total cost is assumed to be 12%.

Monte Carlo Simulation is used to generate 3000 sets of random travel demand for this case. The corresponding total cost is calculated according to equation (5) and (6). The cumulative distributions of total cost for the three design alternatives are compared in Fig 6 (a) and (b). It should be noted that cost is outflow from the perspective of system design. So negative value is used to represent cost in Fig 6 (a) and (b). Fig 6 (a) presents the cumulative distribution of deterministic design A and flexible design C. It shows that adding flexibility in pedestrian bridge design greatly decreases both maximum total cost (from 98.86 million to 36.63 million) and the expected total cost (from 15.13 million to 10.80 million). Fig 6 (b) compares the cumulative distribution of deterministic design B and flexible design C. It shows that the expected total cost of flexible design is less than deterministic design B (10.80 million vs. 11.35 million). In addition, the maximum total cost is slightly less than deterministic design B (36.63 million vs. 37.54 million).

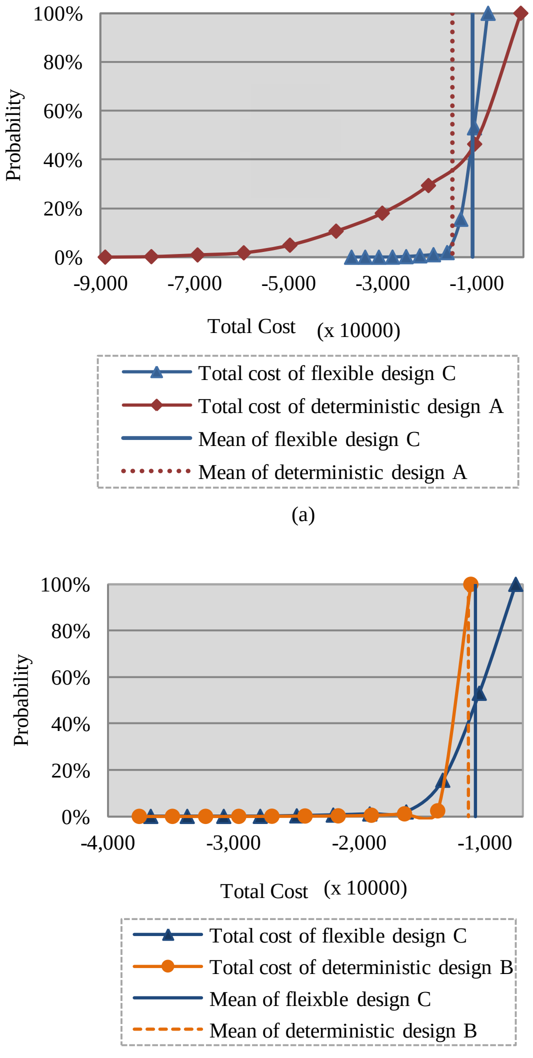

Fig 6: (a) Cumulative distribution of design A and design C
(b) Cumulative distribution of design B and design C

VI. CONCLUSION

In this paper, a sensitivity-based method is proposed to identify where the flexibility should be added in a system. The design variable x is sensitive in the neighborhood of an exogenous factor ef when the exogenous factor ef directly or indirectly affects design variable x. Specifically, the changes of exogenous factor ef can instigate the changes of design variable x. The design variable, influenced by more exogenous factors, is more sensitive, compared to other design variables. The most sensitivity design variables are the potential flexible design opportunities which are selected and identified by exogenous factor searching algorithm and flexible opportunity selection algorithm. Finally, add flexibility in the selected opportunity. A hypothetical HSR system is designed to illustrate how to use sensitivity-based method to identify potential flexible design opportunities. The case study shows that the flexible design strategy can greatly decrease both the maximum total cost and expected total cost, compared with deterministic design strategy.

The proposed approach has the following advantages. Firstly, the proposed approach is more suitable for the system which has a large number of design variables and complex relationships. It is difficult to identify all the relationships among exogenous factors to design variables within these systems. The sensitivity-based method not only considers the direct relationships but also considers the indirect relationships. Therefore, the possible source of uncertainty for particular design variable can be fully investigated. Secondly, the sensitivity of design variable is clearly defined in this paper. The sensitivity of each variable can be quantitatively measured by counting the number of affecting exogenous factors, which can instigate the changes of a particular design variable. Thirdly, the exogenous factor searching algorithm is proposed to quickly measure the sensitivity of each design variable. The potential flexible design opportunities are the design variables, which are selected by the flexible opportunity selection algorithm.

In this paper, we only consider the design variables and their sensitivities for evaluating the flexible design opportunities. However, other factors may also affect the result in real practice, such as the probability that exogenous factor may change in future and the switch cost of changing design variables. All these factors need to be incorporated in future work.

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