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AN APPROACH TO GENERATE FLEXIBILITY IN ENGINEERING DESIGN OF SUSTAINABLE WASTE-TO-ENERGY SYSTEMS

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ABSTRACT

Designing an engineering system that is sustainable both environmentally and economically is a challenging and emergent task. This paper considers embedding flexibility into the engineering design of an upcoming waste-to-energy (WTE) system as a mechanism to ensure better sustainability in long-term lifecycle. A methodology is proposed to identify valuable opportunities to embed flexibility as a way to deal pro-actively with uncertain waste and consumer patterns. The proposed methodology helps to limit the number of flexible design concepts that decision-makers have to consider and analyze in the initial design phase. Application of the proposed methodology is demonstrated through the analysis of novel WTE technology in Singapore based on anaerobic digestion. Result shows that the expected net present value (ENPV) of the flexible design provides a 38.6% improvement over the fixed rigid design in terms of economic lifecycle performance. This design is conducive of better economic sustainability via additional power generation, and better use of resources. Results also indicate that the flexible design can reduce downside risks and capitalize on upside opportunities significantly.

Keywords: sustainability, uncertainty, flexibility, waste-to-energy system, conceptual design

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1 INTRODUCTION

With the increase in population and infrastructure development in cities, building environmentally sustainable cities has attracted great attention from researchers, policy makers and government agencies. One of the critical issues for developing sustainable cities is how to dispose of municipal solid wastes (MSW), and produce energy in an environmental and economical way. Currently, the total amount of MSW is increasing significantly worldwide. However, resources for disposing wastes as well as generating energy are becoming scarce. Taking Singapore for example, the total amount of waste generated in 2011 was 6.9 million tons (National Environment Agency 2011). Compared to the wastes of 1999, there has been an increase of more than 2 million tons during the last decade. Although waste is generated rapidly, only limited landfill capacity (63 million m^3) can be used in Singapore (Bai and Sutanto 2002). In addition, this limited landfill capacity needs to be conserved for future development. This conflicting phenomenon is very common in many mega-cities. In order to reduce the need for new disposal plants and extend the lifespan of landfill, selecting advanced waste-to-energy (WTE) technology as well as designing a sustainable WTE system become a challenging and an emergent task for government agencies and researchers.

One important issue in designing a sustainable WTE system is how to make such system resilient to a changing environment and future uncertainty. Generally, various uncertainties, such as changes in waste generation rate, recycling rate, waste composition and quality, energy price, and material cost may significantly impact the lifecycle performance of WTE system. The design problem here is how to reduce the impact from downside uncertainties (e.g. higher waste production than planned), and how to capitalize on upside opportunities (e.g. more efficient waste recycling technology than planned) for the WTE system, with the net effect of improving overall lifecycle performance. In the literature, flexibility in engineering design provides a way to address this issue. It enables engineering systems – i.e. complex systems for communication, transportation, or energy generation and distribution, like satellite systems, airports, and power plants – to change easily in the face of uncertainty and make the system more sustainable in its operational environment (Fricke and Schulz 2005).

Motivated by the fact that flexibility can help address the challenges of sustainable development, this paper addresses the research problem of how to design more sustainable WTE systems by embedding flexibility in the system design phase. The key contributions of this paper are as follows. First, a novel methodology is proposed to identify the most crucial and valuable design opportunities for embedding flexibility in complex systems. The proposed methodology selects and ranks potential design opportunities by considering the impact of multiple uncertainties, change propagation phenomenon and complex interdependency that exist among the elements of such complex system. Compared to existing methods, the proposed methodology limits and reduces the number of design concepts that decision makers have to generate and evaluate before a detailed design phase and implementation. Second, the methodology of flexible engineering design is applied to analyze an example WTE system, and provide a holistic system-level representation of the system.

2 RELATED WORK

2.1 Flexibility and real options

Flexibility is an important system's attribute to ensure resilience to changing conditions, and ultimately better sustainability. It is closely related to the concept of a real option, which provides the "right, but not the obligation to change a system as uncertainty unfolds" (Trigeorgis 1996). Flexibility has been shown to improve lifecycle performance by 10%-30% compared to standard design and evaluation approaches (de Neufville and Scholtes 2011). Two ways of embedding flexibility in engineering system design are proposed in the literature -- real options "on" project, and real options "in" project (Wang 2005). A real option "on" project treats the whole system as a "black box". It focuses on managerial flexibility, providing decision-makers the options to make strategic decisions at a later stage. A real option "in" project refers to the flexibility within the system, which focuses on how the system components can be changed adaptively to a changing environment.

Currently, most research in flexible engineering design focuses on constructing an appraisal mechanism to evaluate flexibility. The aim is to quantify the benefits of flexibility and further compare it to the additional costs required to enable flexibility. The work done in the Real Option Analysis (ROA) community enables a quantitative evaluation of flexibility in engineering design (Trigeorgis

1996). However, most studies are based on the assumption that the flexible concepts are available a priori. In practice, decision-makers may not be clear where to focus the design effort for flexibility, since a large number of design variables, complex interdependencies and various uncertainty scenarios have to be considered. Nowadays, many researchers realize that where/how to generate flexibility for engineering system is an important task, with the goal of achieving realistic design methodologies. Therefore, it becomes an attractive research topic in engineering design. Motivated by this, this paper focuses on the research area of how to generate flexibility in complex systems. It aims to provide a practical design methodology for identifying flexible design opportunities (FDOs).

2.2 Flexibility generation for engineering design

Flexibility generation can be further classified into two aspects. The first aspect focuses on improving the concept generation phase in response to major uncertainty sources. Various concept generation procedures and methodologies have been proposed. Fricke and Schulz (2005) suggested the design principles of changeability to generate new concepts. Mikaelian et al. (2011) proposed a holistic approach based on the characterization of real options as a mechanism and type, as part of the Integrated Real Options Framework (IRF). Cardin et al. (2012) investigated and evaluated the effects of two educational training procedures and two ideation procedures, in order to systematically guide decision-makers to create concepts for flexibility. Moullec et al. (2012) proposed an architecture generation and exploration method to generate all possible architectures under various constraints. Wang (2005) proposed an optimization screening method to screen out valuable system configurations by exploring the design space for flexibility.

The second aspect focuses on identifying design opportunities to embed flexibility in engineering design. The identification methods are mostly based on design structure matrix (DSM). Suh et al. (2007) proposed change propagation analysis (CPA) to identify multipliers as opportunities to embed flexibility. Kalligeros (2006) proposed sensitivity DSM (sDSM) to look for design variables that are most sensitive to changes in design variables and functional requirements. Bartolomei et al. (2012) extended CPA and sDSM by considering multiple source of uncertainties from technical, human and social domains, and suggested engineering systems matrix (ESM) to select “hot spots”, or good opportunities to insert flexibility.

Although existing methodologies are applicable and effective in different circumstances, several challenging and important issues still need to be considered. First, flexible concept generation methodologies aim to improve the concept generation phase, with the goal of systematically creating better design concepts. However, a large number of feasible concepts are generated and the decision-makers need to analyze and evaluate all the concepts before making decision. Second, the methodologies based on DSM method can provide a clear view of design variables and their complex interdependencies to identify FDOs. However, they have been mostly used for product platform design, and it is unclear how to use them for engineering systems that are typically more complex. In addition, they do not address the issue of considering complex change propagation phenomena. For example, the CPA method considers change propagation in the flexible concept generation process. However, only the direct dependent relationships which are between the neighboring system elements are considered. Third, the methodologies based on DSM methods for identifying FDOs only consider one main uncertainty source. Further research is needed to understand how to identify FDOs when multiple uncertainties are considered simultaneously. This paper addresses some of these issues by suggesting a novel methodology, which extends and merges recent development techniques from the fields of engineering design, change propagation management, and Bayesian network analysis.

2.3 Previous work in WTE system

A comprehensive review of systems analysis techniques in waste management practice is summarized by Chang et al. (2011). Fourteen techniques are fully described and formally classified into two categories: systems engineering models, and systems assessment tools. Currently, the major research topics in waste management are the problems of siting facilities, selecting disposal technologies, and comparing management options. In order to help government agencies improve the design of WTE systems, systems engineering tools such as optimization models, forecasting models and simulation models are used (e.g. Liu et al., 2006). Besides systems engineering models, various systems assessment tools are applied in waste management systems, in order to evaluate their performance after they have been created (e.g. Salhofer et al., 2007).

Research efforts on system optimization and evaluation have been devoted to WTE so far. Yet, limited work has focused on the problem of interdependency representation for the system elements within a WTE system. Existing methodologies analyze the WTE system from an environmental, social and technology domain standpoints, and aim to achieve sustainable solutions. However, to the authors' best knowledge, few studies have analyzed sustainable WTE systems from the perspective of flexible engineering design, considering this as a mechanism to ensure better resilience and sustainability. This paper aims to address the issue of how to generate flexible design concepts for WTE systems and generate better design solutions. The proposed methodology will be explained and applied to select valuable system elements to insert flexibility as a way to deal with an uncertain future, and provide better lifecycle performance. It is argued, indeed, that explicit considerations of uncertainty and flexibility in the early design phases will make better uses of resources later in the operational phase, by planning for careful adaptation to changing conditions (e.g. waste usage and generation patterns, demographics, technology, emissions regulations). This will help reduce the switching cost (i.e. cost associated to exercising flexibility, which changes the system from one state to another) often associated to adaptive mitigation strategies that are more reactive in nature. Overall, this should contribute to creating a system that is more resilient and sustainable for the future.

3 METHODOLOGY

3.1 Initial analysis

The first step focuses on modeling and representing a complex engineering system at a systems-level. The ESM methodology is used for characterizing the source of uncertainties and interdependencies of the system elements. The ESM models engineering system using an adjacency matrix and represents the direct dependent relationships between the neighboring system elements. It captures the dependent relationships between system elements from multiple domains, thus providing a holistic view of the engineering system for designers (Bartolomei et al., 2012). Here, the ESM methodology is extended to model the engineering system by considering how likely one element will change due to a change in neighboring element. The relation and the degree of dependency are represented using a *triggering probability*, which is defined as the probability that a change in the design of one element will lead to a change in a neighboring element. Besides the triggering probability, the prior probability – showing how likely an uncertain scenario will occur in the future – and the switching cost – representing the cost of system elements related to the change – are analyzed. All domain information for constructing the system-level representation is extracted based on experts' knowledge and historical data. The likelihood of change can be elicited using standard probability elicitation techniques (Morgan and Henrion 1990).

3.2 Bayesian network model development

The second step of the methodology focuses on modeling complex interdependencies within an engineering system. Here, changes in system elements and their impacts on other system elements are considered, considering as well indirect connections. Therefore, a single change may ultimately transform and propagate across a large portion of the system, and thus cause significant impact to the system. In order to thoroughly and holistically model the change mechanism within the engineering system, the impact of change propagation should be taken into account. In this paper, such impact is measured quantitatively by a *combined conditional probability*, defined as the change probability of one element given the change of other elements with either direct or indirect dependent relationships.

Complex interdependencies of system elements are modeled using a Bayesian network methodology. The system elements, which are analyzed in the ESM matrix, are represented as nodes, and the direct relationships between elements are modeled as edges in the Bayesian network. The prior probability and triggering probability are used to construct the conditional probability table (CPT) for each node in the network. Two issues are addressed when modeling an engineering system using the Bayesian network. First, cyclic dependencies are commonly observed within the engineering system. For example, suppose three system elements A, B, and C have dependent relation as $\mathrm{A} \rightarrow \mathrm{B} \rightarrow \mathrm{C}$. A cyclic dependency occurs, if the system element A depends on C. This cyclic dependency cannot be modelled using Bayesian network methodology, since a directed acyclic graph is typically assumed. To solve this problem, direct dependencies from uncertainty sources to system elements are preserved. Other dependencies, which have a lower triggering probability, are removed if a cycle is observed. The second issue is that it is easy to specify the triggering probability of each system element under the change of one parent node, since only one dependent relationship is considered between two system elements. However, it is difficult to obtain the distribution conditioned on all parent nodes. Therefore, the question is how to construct and estimate the CPT using available data. In order to obtain such conditional probabilities between neighboring elements, the "noisy-OR" assumption, which assumes that all causes (parents) are independent in terms of their influence on the child, is applied. A detailed example of inferring the combined conditional probability is described in section 4.

3.3 Risk prediction and measurement

The third step focuses on predicting the risk of each system element if a change is triggered and propagated within the system. The risk here is measured by the combined conditional probability, which is inferred using the Bayesian network, and the switching cost, which is extracted from the initial analytical step. The risk measurement methodology used here is adapted from risk management theory and change prediction method (Clarkson et al., 2004).

First, the risk received by each system element when a change is triggered by uncertainties is measured. This risk is denoted as $R_{s_i}^{Received}$, and is calculated by equation (1):

$$R_{s_i}^{Received} = P_{s_i|\forall\, u_j \in D^k} C_{s_i} \tag{1}$$

where s_i represents the i^{th} system element, D^k is a set of uncertainties for scenario k, u_j is one of the uncertainties in D^k, and C_{s_i} is the switching cost for system element s_i. The term $P_{s_i|\forall\, u_j \in D^k}$ represents the conditional probability that system element s_i will change caused by a change in uncertainty scenario k, via both direct and indirect links. This combined conditional probability is different from the probability in the CPT, since both the direct and indirect relationships are considered. It can be inferred by the Bayesian network model. Overall, $R_{s_i}^{Received}$ indicates the degree of the risk received by system element s_i, due to the impact of uncertainties.

The second measurement is to predict the risk caused by system element s_i, if system element s_i is changed. Let us assume that a flexible option is embedded in system element s_i in the initial design phase. If one implements a flexible option to respond to uncertainty, the system element s_i will change and this change may further propagate to other child nodes. The problem is how to measure the risk on these child nodes downstream, due to a change of system element s_i upstream. This can be calculated by equation (2):

$$R_{s_i}^{Generated} = \sum\nolimits_{s_j \in D_{s_i}} (P_{s_j|s_i, \forall u_j \in D^k} - P_{s_j|\forall u_j \in D^k})\, C_{s_j} \tag{2}$$

Here D_{s_i} is a set of system elements which contain all the child nodes of system element s_i, $P_{s_j|s_i, \forall u_j \in D^k}$ is the combined conditional probability of a change in system element s_j given a change in system element s_i under scenario $k, s_i \neq s_j$, $P_{s_j|\forall u_j \in D^k}$ is the combined conditional probability of s_j conditioned on the uncertainties in scenario k. The difference between the two probabilities is the state of the parent node s_i. The subtraction here represents the increased probability of child node (s_j), due to a effect of changing the parent note s_i. $R_{s_i}^{Generated}$ indicates the degree of the risk generated by the system element s_i, when the flexible option is implemented.

3.4 System elements ranking and selection

The last step focuses on ranking the system elements and selecting the most valuable system elements to embed flexibility. The most valuable system elements are referred as FDOs in this paper, and they are selected based on the risk indicators measured in the third step in Section 3.3. The system elements that have high $R_{s_i}^{Received}$ and low $R_{s_i}^{Generated}$ are suitable for flexible design. This is because that the elements with high value of $R_{s_i}^{Received}$ are susceptible to uncertainties and the cost of exercising the change will be high. In addition, the elements with low $R_{s_i}^{Generated}$ implies that they may not cause significant impact to the whole system if a change occurs to such elements. Therefore, the elements with high $R_{s_i}^{Received}$ and low $R_{s_i}^{Generated}$ should be made easier to change to save the switching cost in the future. This can be accomplished by embedding flexibility.

The change propagation index (CPI) methodology by Suh et al. (2007) inspires the risk susceptibility index (RSI) proposed here, calculated via equation (3):

$$RSI_{s_i} = R_{s_i}^{Received} - R_{s_i}^{Generated} \tag{3}$$

The higher RSI_{s_i} is, the more suitable the corresponding system element is to embed flexibility.

4 CASE STUDY

4.1 Identify FDOs for Singapore's upcoming anaerobic digestion WTE system

In Singapore, there are currently only four incineration plants and one landfill to manage food and other waste. Although the total effective incineration capacity of the four existing WTE systems is sufficient to handle all wastes currently generated, advanced waste disposal systems are needed to handle increasing waste generation in the future. A potential technology to dispose waste is anaerobic digestion, which has high efficiency in energy recovery process and has been widely used in European countries. Applying anaerobic digestion technology in Singapore is a potential solution to complement the existing incineration plants. Therefore, this case study aims to investigate how to embed flexibility in an upcoming anaerobic digestion WTE system in the initial design phase.

Figure 1 shows the under development ESM representation of the WTE system in Singapore. It summarizes the dependent relationships of elements from five system domains. For simplification, the triggering probabilities in this case are classified and represented into three levels. The numbers in Figure 1 represent the likelihood and dependent relationships. The higher the number, the stronger the dependence between the system elements. For example, the government (T_1) strongly controls the strategy for a WTE company (T_3) by issuing new policies and regulations. Therefore, the triggering probability $p_{T3|T1}$, which represents the probability that element T_3will change triggered by a change of T_1, is assigned value 0.9. On the other hand, the operation and management of the WTE company—i.e. the amount of waste digested annually, the amount of residues disposed to landfill and the electricity generated by digesting waste, may impact the decision of the government agency (T_1). However, this impact cannot control government's decision, and the way to impact the decision is not clear. Therefore, the corresponding triggering probability is $p_{T3|T1}$ = 0.3. An empty cell shows no explicit dependence expected between the two system elements, such that change of one component does not trigger any more changes. All the information showed in Figure 1 is estimated and analyzed based on expert communications and publicly available information (e.g. Rogoff and Screve 2011).

ESM		System drivers			Stake-holders			Objective				Functions					Objects								
		S1	S2	S3	T1	T2	T3	O1	O2	O3	O4	F1	F2	F3	F4	F5	B1	B2	B3	B4	B5	B6	B7	B8	B9
System drivers	Total amount of generated waste (S1)				0.6	0.6																			
	Recycling rate (S2)				0.6	0.6																			
	Rate of disposed organic waste (S3)				0.3	0.6																			
Stakeholders	Government (T1)					0.3	0.3																		
	Public (T2)				0.3																				
	Operation company (T3)				0.9																				
Objectives	Eliminating the use of land use (O1)	0.6			0.9																				
	Maximize waste to energy generation rate (O2)				0.9		0.6																		
	Minimize emission during conversion (O3)				0.9																				
	Achieve a clear and safety environment (O4)				0.9	0.3	0.3																		
Functions	To provide service of recycling waste (F1)							0.9																	
	To provide service of collecting waste (F2)										0.9														
	To dispose waste (F3)							0.9		0.9															
	To generate power (F4)								0.9																
	To control emission (F5)									0.9	0.9														
Objects	Vehicle (B1)	0.6											0.9												
	Materials recovery facility(MRF) (B2)		0.6									0.9							0.6						
	Recycling bins (B3)	0.3	0.6									0.9													
	Landfill (B4)	0.3												0.9											
	Pre-processing equipment (B5)													0.9										0.6	
	Major tankage (B6)	0.6	0.6	0.6										0.9											
	Power generator (B7)														0.9							0.6			
	Digestion control system (B8)	0.6	0.6	0.6										0.9											
	Flaring and odor control (B9)															0.9									

Figure 1. ESM representation with triggering probability for WTE system

Table 1 lists the initial cost for developing a WTE system in Singapore. The designed capacity of the system is 550 tons per day. Since there is currently no anaerobic digestion system in Singapore, the initial cost is based on historical data from other countries (e.g. Bumpus 1996 and RIS international Ltd 2005). The switching cost of each system element is assumed to be 50% of the initial cost. Take waste collection vehicle for example, the switching cost means the cost for buying more vehicles to collect the additional wastes that exceed the estimated capacity in the initial design. In this case study, the switching costs are normalized with respect to the maximum value of each system element. The normalized switching cost is used in the risk measurement process. It should be noted that the waste management policy in Singapore is to extend the lifespan of Semakau Landfill to 50 years, and the final target is to strive towards zero landfill. Therefore, no flexible option is currently considered for landfill in this case, and no switching cost for landfill is shown in Table 1.

Table 1.Initial cost and switching cost of WTE system

System elements	Initial cost (S$)	Switching cost (S$)	Normalized Switching cost
Waste collection vehicle	1,000,000	500,000	0.078
Materials recovery facility (MRF)	7,925,902	3,962,951	0.619
Recycling bins	138,889	69,444	0.011
Landfill	19,312,000	-	-
Pre-processing equipment	3,325,590	1,662,795	0.260
Major tankage	12,814,402	6,406,651	1.000
Power generator	8,177,039	4,088,519	0.638
Digestion control system	9,781,147	4,890,573	0.763
Flaring and odor control	1,027,020	513,510	0.080

After the WTE system has been analyzed, the Bayesian network model is constructed by removing cycles and estimating CPT. Figure 2 is a screenshot from Netica[1] showing a prototype network model. Visualization of the network includes the name of each node and the state name for each node. Here, each node has only two states. C means that a characteristic of the system element has to change, while S means the characteristic stays the same within a range, and may not impact other system elements. For example, state C for amount of waste generated (top left corner) means that waste levels are significantly increased to a specific value (e.g. larger than the designed capacity). On the other hand, state S means the amount of waste staying within a range. And the probability of the element being stable is 0. The dependencies between nodes are shown as edges and the combined conditional probabilities are shown as percentages. Figure 2 shows the updated probability distributions of all the remaining nodes, assuming that three system elements – amount of waste, recycling rate and ratio of organic waste – are changed simultaneously. It can be inferred that the system elements major tankage and digestion control will be changed with combined conditional probability of 99.2%.

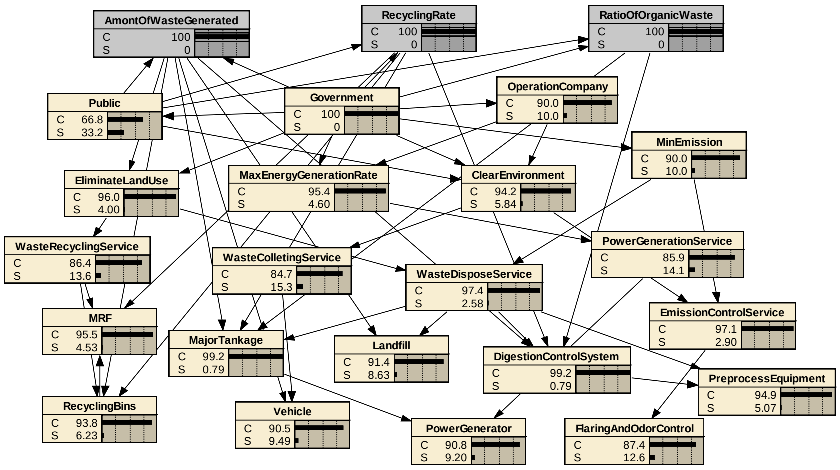

Figure 2. Bayesian network model of WTE system with three system elements changed

For simplification, it is assumed that the major source of uncertainty is from an environmental domain. Specifically, only system elements from the systems drivers' domain in the ESM are characterized as main uncertainty drivers. The WTE system is analyzed under four scenarios: 1) only the amount of waste is changed, 2) only the system element of recycling rate is changed, 3) only the system element

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[1] More information is available on Netica's website: http://www.norsys.com/

of ratio of organic waste is changed, and 4) the three system elements in scenarios 1-3 are changed simultaneously, as shown in Figure 2.

System elements from the object domain in the ESM are referred as system components in this paper. As example, the focus is on identifying valuable system components for flexibility in this particular domain. The combined conditional probability of each system component is inferred in the four scenarios described above by the Bayesian network model. Together with the information of the switching cost shown in Table 1, the system component can be quantitatively ranked by the RSI value. Table 2 summarizes the ranking information for each system component. It suggests that major tankage (B_6) has the highest value across the four scenarios, and is therefore as a valuable opportunity for embedding flexibility. The next element is the digestion control system, not analyzed here for brevity.

Table 2. RSI for each system components across the four uncertainty scenarios

BN nodes	Scenario 1 P(s_1=C)=100% P(s_2=C)=0 P(s_3=C)=0	Scenario 2 P(s_1=C)=0 P(s_2=C)=100% P(s_3=C)=0	Scenario 3 P(s_1=C)=0 P(s_2=C)=0 P(s_3=C)=100%	Scenario 4 P(s_1=C)=100% P(s_2=C)=100% P(s_3=C)=100%
B_1	0.07	0.06	0.06	0.07
B_2	0.53	0.58	0.48	0.59
B_3	-0.04	-0.01	-0.11	0.00
B_5	0.24	0.24	0.24	0.25
B_6	0.95	0.94	0.94	0.99
B_7	0.58	0.58	0.58	0.58
B_8	0.72	0.72	0.72	0.76
B_9	0.07	0.07	0.07	0.07

4.2 Economic evaluation

This subsection evaluates the proposed methodology by comparing the lifecycle performance of the flexible designs generated using the proposed approach versus a baseline, fixed design. The fixed design is set as the best capacity design based on deterministic predictions, and without considerations of possible changes in future. In the flexible design considers the system components *major tankage* and sets a small tankage capacity in the initial design phase with the flexibility to expand capacity in the future. The total amount of waste and recycling rate are modeled using Geometric Brownian Motion, while the ratio of organic waste is modeled using mean reversion theory. In this case, the decision rule is to expand the capacity if the amount of disposed organic waste is larger than the designed capacity in two consecutive years. The net present value (NPV) of these two design concepts is calculated according to equation (4):

$$NPV = \sum_0^{30} \frac{CF_t}{(1+r)^t} \text{ where } CF_t = R_D^t + R_E^t - C_{init} - C_{O\&M}^t - C_{SC}^t - C_{fle} \quad (4)$$

CF_t is the cash flow at year t, R_D^t presents the revenue for disposing of the wastes at year t, R_E^t presents the revenue for selling recovered electricity at year t, C_{init} is the initial cost for developing the WTE system, $C_{O\&M}^t$ presents the operation and management cost at year t, C_{SC}^t is the switching cost at year t, C_{fle} is a premium for acquiring flexibility. C_{fle} is roughly approximated as 10% of the initial cost for system component of *major tankage*. It should be noted that C_{SC}^t and C_{fle} are set to 0 in the fixed design. In this case, r is the annual discount rate and is assumed to be 8%.

The anticipated lifecycle performance is measured using expected (or average) NPV (ENPV) for these two design concepts by simulating 1,000 trials for total amount of wastes, recycling rate, and ratio of organic wastes. Each combination produces different cash flows and NPV, as captured by equation (4). Table 3 summarizes the key statistics for the flexible design and benchmark design, and Figure 3 shows the NPV distribution and ENPV for these two designs. Results show that the flexible design outperforms the benchmark design, with the overall effect of improving the system's ENPV compared to a fixed, rigid design. First, ENPV is larger than for the benchmark design by 38.6%, showing clear improvement over the benchmark design. There is a 5% chance – the value at gain (VAG) or percentile 95 value (P95) – that NPV values generated by the flexible design will be greater than S$139.00 million, also significantly larger than that of the benchmark design. From the perspective of value at risk (VAR) – a measure or possible downside conditions – the benchmark has 5% chance to generate NPV values less than S$ 12.80 million. This is much less than that of the flexible design, showing the latter is also good at alleviating the impacts from downside senarios. Smaller tankage capacity also incurs less cost initially than full capacity.

Table 3. Summary of key statistics for flexible design and benchmark design (S$ million)

	Flexible design in major tankage	Benchmark Design	Best
ENPV	95.16	68.65	Flexible design
P5	45.90	12.80	Flexible design
P95	139.00	108.00	Flexible design
Std dev.	27.91	29.96	Flexible design
Initial Cost	46.90	63.90	Flexible design

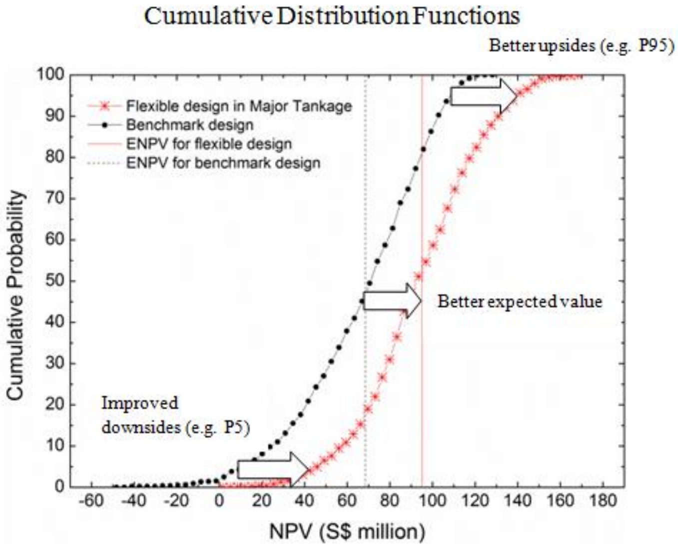

Figure 3. Cumulative probability of NPV for flexible and benchmark designs

5 CONCLUSION

This paper proposes a methodology to identify valuable opportunities to embed flexibility in complex engineering system design. This methodology integrates Bayesian network methodology into the engineering system design, and effectively models complex change propagation within multiple domains of an engineering system. It builds upon and improve existing methodologies, which only consider direct neighboring relationships in the generation of flexible design concepts. The proposed methodology selects and ranks a set of system elements by predicting and analyzing the risk of change propagation. The ranking information of system elements limits the number of flexible design concepts to analyze at an early conceptual stage, in contrast to other concept generation methods available in the literature. Furthermore, the ranking information provides clear guidance to designers and decision-makers, especially when they have limited analytical resources available.

The proposed methodology is applied as demonstration to the analysis of a potential WTE system in Singapore. Result shows 38.6% ENPV improvement as compared to a fixed, rigid system when flexibility is embedded in the *major tankage* system component. This supports the view that the system component of *major tankage* is a valuable choice for embedding flexibility.

Many opportunities for future research exist by addressing the limitations of this work. Future work may look into a holistic performance metric to evaluate the WTE system from a sustainable perspective, complementary to the lifecycle economic perspective taken here. The ranking information of design opportunities provided by the proposed methodology could be further validated by conducting further analysis, and collaborating with academics and industry in the actual design and implementation. The proposed methodology can be compared with other flexible concept generation methodologies, such as CPA by Suh et al. (2007), prompting and explicit training by Cardin et al.

(2012), or the IRF by Mikaelian et al. (2011, 2012) to determine which ones are most effective, depending on context and resources.

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