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Optimization of System Maturity and Equivalent System Mass for Exploration Systems Development Planning

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Abstract

Begin the paper with an abstract (50 to 150 words) that summarizes the topic and important results in the paper. **Include the abstract in the manuscript electronic format.**

Introduction

The Exploration Systems Mission Directorate of the National Aeronautics and Space Administration (NASA) is currently pursuing the development of the next generation of human spacecraft and exploration systems throught the Constellation Program. This includes, among others, habitation technologies for supporting lunar and Mars exploration. The key to these systems is the Exploration Life Support (ELS) system that composes several technology development projects related to atmosphere revitalization, water recovery, waste management and habitation. The proper functioning of these technologies is meant to produce sufficient and balanced resources of water, air, and food to maintain a safe and comfortable environment for long-term human habitation and exploration of space.

The development of the ELS system, while investigating advanced technology concepts, also builds upon legacy technologies generated from prior NASA programs, e.g. Apollo, Space Shuttle, and International Space Station (ISS). With varying degrees of technology maturity in the development of this system, many challenges arise in the development and testing of the integration links among the technologies as well as maintaining an understanding of the maturity of the whole system. The need to have the capability to express the maturity of the system as a whole and monitor the progression of the technologies and their supporting integrations becomes a complex challenge (Jain, et al., 2008). Likewise, determining which technologies should receive continued investment in achievement of a system's mission objectives has strategic and engineering implications (Sandborn, et al., 2003). The balancing of technology development and integration efforts in the achievement of a system's objectives is not new to NASA or any organization (Buede, 2000). Yet, the assessment of these efforts via effective and efficient use of metrics has been a sustained challenge (Tetlay, et al., 2009).

Within NASA, two metrics have been researched or implemented to assess the developmental maturity of a technology or to determine its relative impact on the system's mission, i.e. Technology Readiness Level (TRL) and Equivalent System Mass (ESM).

TRL has been traditionally used within NASA as an assessment of the maturity of evolving technologies prior to incorporating them into a system or sub-system on a scale of 1 to 9 (9 indicating highest level of maturity). The original TRL was a by-product of the NASA post-Apollo era as an ontology for contracting support (Sadin, et al., 1989). It later became a standard metric for communication of technologies' developmental status (Mankins, 2002). Other government agencies and contractors have since adopting the TRL scale with specific variations (e.g., Department of Defense, Department of Energy). However, TRL, by definition, can only refer to the maturity of the technologies but not the system as a whole. For example, it neglects the integration links among the technologies, which tend to be more complicated and multi-dimensional (Sauser, et al., 2006). To address this shortcoming, Gove (2007) and Sauser et al (2009a, 2009b) introduced the concept of an Integration Readiness Level (IRL), also a 1 to 9 scale. When combined with TRL, Sauser et al. (Sauser, et al., 2008a, Sauser, et al., 2008b) were able to calculate a System Readiness Level (SRL) and plot it against a system development lifecycle to evaluate the status of each subsystem and the system as a whole.

Likewise, ESM has been used to evaluate the trade options (Russell, et al., 2007) in ELS systems in order to meet requirements of minimizing launch cost, as related to the mass, volume, power, cooling and crew-time needs (Levri, et al., 2000, Levri, et al., 2003a). Levri and Drysdale (2003a) further explained that the tradeoff between the ESM of two technology options may be so small that further analysis is needed by using a metric such as TRL. It is the focus of this paper to utilize the work of Sauser, et al. (2008b) in SRLs to enhance the capability of ESM as Levri and Drysdale (2000) proposed in utilizing TRL as an additional decision metric. We will also expand upon this approach by utilizing an optimization model that seeks to maximize its readiness (i.e. SRL, IRL, and TRL) given a budgetary allowance expressed in terms of ESM. We will conclude with an articulation of this optimization model utilizing a generic ELS system.

Exploration Life Support Systems

Exploration Life Support is a technology development project under the NASA Exploration Technology Development Program (ETDP) (NASA, 2009). Aside from the development of system solutions for atmosphere revitalization, water recovery, waste management, and habitation engineering, it has threaded efforts in systems integration, modeling and analysis, and validating and testing as well as being an integral part of the Exploration Systems Mission Directorate of NASA. The motivation of the development of an ELS system is to support the human exploration of the moon and beyond, e.g. Mars. The ELS project is guided by the following objectives (NASA, 2009):

1. Develop and mature life support system technologies that meet mission requirements and fill capability gaps or significantly improve the state-of-the-art;

2. Develop technologies for infusion by the date for each vehicle's Preliminary Design Review, approximately six years before flight. Provide information by System Requirements Review and at other interim milestones; and

3. Develop technologies that are efficient with respect to resource requirements (mass, power, heat rejection, volume, crew time, consumables) and are safe and reliable.

While there are many technology options to achieve the mission objectives of an ELS system, Figure 1 represents a simplified concept architecture of an ELS system, which will be used to illustrate the application of the proposed quantitative analysis in this paper. The technologies depicted in Figure 1 are:

Crew Habitat: technology functions include crew functionality, comfort, and quality of life to ensure crew productivity.

Air Revitalization: technology functions include CO_2 partial pressure control; moisture removal; trace chemical contaminant control; particulate matter removal and disposal; atmospheric gas supply, storage, conditioning, and distribution; resource recovery, storage, conditioning, and recycling.

Food Processing: technology functions include the processing, storage, and preparation of food.

Biomass Production: technology functions include the growth of higher plants for the purpose of supplying food and revitalizing air.

Waste Processing: technology functions include water/resource recovery, safening and stabilization, disposal and containment, waste/trash volume reduction, and odor control.

Water Processing: technology functions include recover of approximately 90% of wastewater to potable water quality via physical-chemical methods.

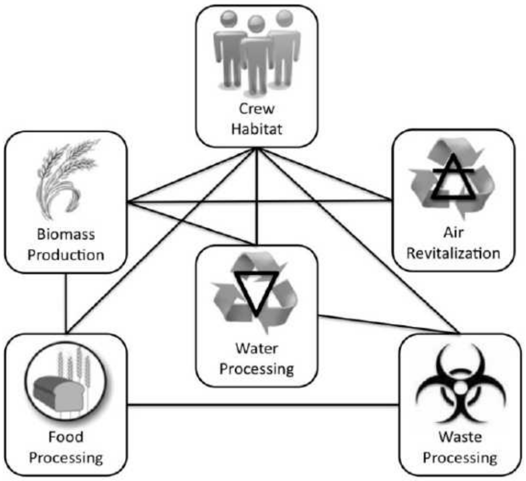

Figure 1: Exploration Life Support System Concept Architecture

System Readiness Level

Despite the utility and value of the TRL as a metric for determining technology maturity before transitioning into a system, TRL was not intended to address systems integration or to indicate that the technology will result in successful development of a system. Additionally, when TRL is applied to components within a complex system, the model of using individual technology maturity as a measure of readiness to integrate into system development can become confounded. Similar problems also become apparent with many other technology development tools when applied in a systems context.

This lack of adequate systems-level development monitoring tools and methodologies has resulted in several complex development programs with significant shortfalls. Given the emerging requirements for a measure of complex system readiness, the Systems Development & Maturity Laboratory (SD&ML) was the first to propose the concept of a SRL that would incorporate a TRL and an IRL for determining system lifecycle maturity.

Under this method, TRL evaluations for each technology and IRL evaluations of each integration are combined using matrix mathematics (explained in detail later) to produce a comprehensive assessment where each technology within the system is weighted according to all of its integrations and then rolled up to a system level. It is important to emphasize that the SRL is not a quantitatively defined rating system, but is instead an analytical combination of the TRL and IRL scales. In others words, the SRL output is purely a function of the TRL and IRL inputs.

The SRL scale is calculated by using a normalized matrix of pair-wise comparisons of TRLs and IRLs that reflects the actual architecture of the system. Briefly stated, the IRL matrix is obtained as a symmetric square matrix (of size $n \times n$) of all possible integrations between any two technologies in the system.

For technology integration to itself, perfect integration is assumed (IRL= 9) while an IRL of zero is used when there is no integration between two elements. On the other hand, the vector TRL defines the readiness level of each of the technologies in the system. The calculation of the SRL has also gone through a series of refinements and the most recent thorough discussion has been presented by Sauser et al (2008a). In its current form, the SRL is calculated as

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \ldots \\ SRL_n \end{bmatrix} = \begin{bmatrix} (IRL_{11}TRL_1 + IRL_{12}TRL_2 + \ldots + IRL_{1n}TRL_n)/m_1 \\ (IRL_{21}TRL_1 + IRL_{22}TRL_2 + \ldots + IRL_{2n}TRL_n)/m_2 \\ \ldots \\ (IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \ldots + IRL_{nn}TRL_n)/m_n \end{bmatrix}$$

where $IRL_{ij}=IRL_{ji}$

and

$$SRL = \frac{SRL_1 + SRL_2 + \ldots + SRL_n}{n}$$

where m_i is the number of integrations with technology i plus its integration to itself. With the ability to assess both the technologies and integration elements along a numerical maturation scale, the next challenge was to develop a metric that could assess the maturity of the entire system under development. Therefore, the SD&ML has described how using a normalized matrix of pair-wise comparisons of TRLs and IRLs for any system under development could yield a measure of system maturity. More recently, the SD&ML has described the formulation and application of the SRL as a metric to determine the maturity of a system and its status within a developmental lifecycle (Sauser, et al., 2008a, Sauser, et al., 2008b). Figure 2 is a representation of the SRL scale against the *NASA Project Life-Cycle Process Flow for Ground and Flight Systems* (NASA, 2007). Figure 2 will be used in later discussions of the application of the SRL. The rationale behind the SRL developed by the SD&ML is that in the development lifecycle, one would be interested in addressing the following considerations:

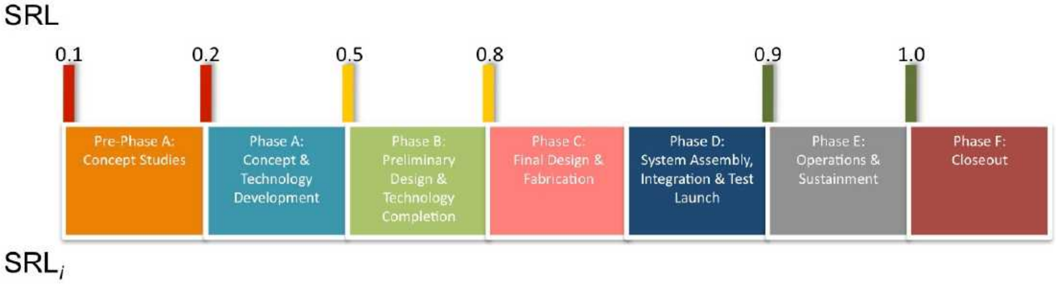

Figure 2: NASA Project Life-Cycle Process Flow for Ground and Flight Systems with SRL

- Quantifying how a specific technology is being integrated with every other technology to develop the system.
- Providing a system-wide measurement of readiness.

Therefore, SRL is more than purely a qualitative assessment. It requires the user to define the element level contributions of the multiple technologies and integrations that makeup the system. In this way, it allows managers to evaluate system development in real-time and take proactive measures by examining the status of all elements of the system simultaneously. Furthermore, the methodology is highly adaptive to use on a wide array of system engineering development efforts and can also be applied as a predictive tool for technology insertion trade studies and analysis.

Equivalent System Mass

ESM was first defined in 1997 as a metric for comparing technology options for the Advanced Life Support project (now referred to as ELS) (Drysdale, 2003). It allowed for the trade-off of mass, volume, power, cooling and crew time based on a single mass value. The fundamental premise was that a mass value could be equated to launch cost (e.g. it cost $10,000 per pound to launch a payload on the Space Shuttle), thus allowing for the optimization of technology options to achieve mission objectives. The motivation for this was that dollar cost for technology development (Drysdale, 2003):

- can be politically sensitive;
- are not generally released;
- do not always include all cost; and
- tend to be complex and dynamic.

ESM allowed for cost to become an independent variable and not have a direct influence on a trade analysis.

The use of equivalent weight and power penalties for space payload options was first introduced by Trusch and Brose (1972). From that time much of the development of equivalent weight as an options metric was done by Drysdale (2003, 1999) further expanded by Levri et al. (2003a, Levri, et al., 2000), and demonstrated as a decision support tool by Rodriguez et al. (2004) and Russell (Russell, et al., 2007). ESM is calculated as

$$ESM = M + L + V * eqV + P * eqP \\ + C * eqC + CT * D * eqCT$$

where: ESM = equivalent system mass value of the system of interest [kg], CT = total crew time requirement for operation and maintenance of the system [CM-h/day], D = duration of the mission segment of interest [day], and eqCT = mass equivalency factor for the crew time support [kg/CM-h]. For a detailed explanation and guidance on ESM see (Levri, et al., 2003b).

While ESM adds value to the trade analysis of technology options for space missions, it is still noted that it should not be a stand alone metric and additional metrics that evaluate the developmental status of a technology would be of added value, e.g. TRL (Rodriquez, et al., 2004, Russell, et al., 2007, Drysdale, 2003).

In the next section we will combine the two metrics just described, i.e. SRL, ESM, to formulate a constrained optimization model to demonstrate how these two metric can make a more informed decision as opposed to their functioning independently.

Constrained Optimization Model

SRL was first used in a constrained optimization model by Sauser and Ramirez-Marquez (2009c) to provide information about which technologies and integration links to advance to which maturity level such that the maturity of the system is maximized based on the amount of limited resources made available to a development project. In this paper, a similar optimization model is applied to the development of an ELS system to illustrate how SRL can be used to plan its development. Since SRL itself is based on the TRL and IRL values of the system's components, it measures the overall readiness of the system under development. As such, the systems engineer or program manager who is concerned with utilizing the budget allocated for the system can now set development goals such that the maximum amount of system readiness is achieved. In order to execute the development required to have maximum SRL value, it is necessary to know how to utilize the resources optimally. That is, the systems engineering or program manager must determine which of the system components should be matured to what levels so that he/she can allocate the available resources accordingly. To address these concerns, we are proposing Model ESM_SRLmax as an optimization model whose objective is to maximize SRL (a function of technology and integration development) while keeping the launch cost (expressed in terms of ESM) within an acceptable level. The general mathematical form of the model follows:

Model ESM_SRLmax

*Maximize: SRL (**TRL, IRL**)*

*Subject to: ESM(**TRL,IRL**) ≤ esm*

The matrices **IRL** and **TRL** of the model contain the decision variables. Each of these variables is integer valued and bounded by (IRL_i,9) and (TRL_i,9), respectively. That is, the TRL/IRL for the i^{th} component cannot be below its current level or above perfect technology or integration development (IRL or TRL = 9). The objective function of Model ESM_SRLmax of the system is a function of the decision variables, which dictate how the different levels for both TRL, and IRL are improved. The left hand side of the inequality defined by functions ESM represents the ESM as a function of the improved technologies' TRL and IRL, and the right hand side indicates the total amount allowed for ESM. Since the ESM is an indicator of the needed launch cost, the model tries to maximize the system maturity while under the ESM allowance, and thus meet the cost constraint.

To completely characterize the decision variables, it is necessary to introduce the following transformation:

$$y_i^k = \begin{cases} 1 & \text{If } TRL_i = k \\ 0 & \text{otherwise} \end{cases} \quad \text{and}$$

$$x_{ij}^k = \begin{cases} 1 & \text{If } IRL_{ij} = k \\ 0 & \text{otherwise} \end{cases} \quad \text{for } k=1,\ldots 9$$

Notice that based on these binary variables, each of the possible normalized TRL and IRL in the system can be obtained as:

$$TRL_i = \frac{\sum_{k=1}^{9} k y_i^k}{9} \quad \text{and} \quad IRL_{ij} = \frac{\sum_{k=1}^{9} k x_{ij}^k}{9} \quad \text{and}$$

SRL$_i$ is transformed to:

$$SRL_i = \frac{1}{m_i}\left[\frac{\left(\sum_{k=1}^{9} kx_{i1}^k\right)\left(\sum_{k=1}^{9} ky_1^k\right)}{81} + \frac{\left(\sum_{k=1}^{9} kx_{i2}^k\right)\left(\sum_{k=1}^{9} ky_2^k\right)}{81} + \ldots + \frac{\left(\sum_{k=1}^{9} kx_{ij}^k\right)\left(\sum_{k=1}^{9} ky_j^k\right)}{81} + \ldots + \frac{\left(\sum_{k=1}^{9} kx_{in}^k\right)\left(\sum_{k=1}^{9} ky_n^k\right)}{81}\right]$$

$$= \frac{\sum_{j=1}^{n}\left(\sum_{k=1}^{9} kx_{ij}^k\right)\left(\sum_{k=1}^{9} ky_j^k\right)}{81 m_i}$$

The model belongs to the class of binary, integer-valued, non-linear problems. For the ELS system with *6* technologies containing *10* distinct integrations, and assuming all technologies and integrations are at their lowest levels, there can be as many as 9^{6+10} potential solutions to the model. Evaluating each possible solution is prohibitive so to generate a more timely optimal solution, a meta-heuristic approach developed by Ramirez-Marquez and Rocco (2008) is applied to the ELS system. This approach, called Probabilistic Solution Discovery Algorithm (PSDA), has the capability of producing quasi-optimal solutions in a relatively short period of time. However, it must be mentioned that the results cannot be proven to be the optimal solution. This is because by taking a probabilistic approach, the algorithm can only select subsets of the entire feasible set from which to find a solution. Every time the algorithm is run, a different subset is selected. Nevertheless, prior tests have indicated that PSDA results tend to be better than results from alternative meta-heuristic approaches (Ramirez-Marquez, et al., 2007).

As used in the solution of the maximization problem, after the algorithm is initialized, it follows three inter-related steps:

- Strategy Development – a Monte Carlo simulation is used to identify to what potential TRL or IRL levels the technologies and links can be advanced or matured;
- Analysis – each potential solution is analyzed by calculating its associated SRL and ESM;
- Selection – through an evolutionary optimization technique, a new optimal set of technologies and integration links (with their corresponding TRLs and IRLs) is chosen (based on the SRL and ESM values).

During Strategy Development, based on the probabilities defined by vectors $\boldsymbol{\gamma}_{iu}$ and $\boldsymbol{\gamma}_{iju}$, the simulation is used to generate a specified number (defined by V) of potential designs, $\mathbf{TRL}_u^v$ and $\mathbf{IRL}_u^v$ (v=1,..,V). For each technology i, γ_{iu}^k (the k^{th} element of vector $\boldsymbol{\gamma}_{iu}$) defines the probability that at cycle u, the TRL of such a technology will increase its current readiness to level k (i.e. $\gamma_{iu}^k = P(y_i^k = 1)$). Similarly, γ_{iju}^k defines the probability that at cycle u, the IRL between the ith and jth technologies will increase its actual readiness to level k (i.e. $\gamma_{iju}^k = P(x_{ij}^k = 1)$). This step also contains the stopping rules of the algorithm. In essence, the first rule, which is used in this paper, allows the user to set a specific number of cycles. The second rule dictates the algorithm to be stopped once both vector $\boldsymbol{\gamma}_{iu}$ and $\boldsymbol{\gamma}_{iju}$ can no longer be updated (i.e. all initial "appearance" probabilities are either zero or one). In the context of this algorithm a cycle is understood as every time the value u is updated.

The second step, Solution Analysis, implements the approach discussed in Sauser et al. (2008a) and previously summarized to obtain the SRL, and the ESM of the development associated with each of the potential system design, $\mathbf{TRL}_u^v$ and $\mathbf{IRL}_u^v$.

The final step in the algorithm penalizes the SRL of the potential designs generated in cycle u whenever they violate the ESM constraints. The solutions are then ranked in decreasing order of magnitude with respect to the penalized SRL. Then, the best of these solutions is stored in set K and finally, a subset of size S of the ranked feasible solutions, is used to update the probabilities defined by the vectors γ_{iu} and γ_{iju}. These new vectors are re-evaluated in Step 1 to check for termination or for solution discovery. Finally, when the prescribed number of cycles has been reached, the best solution in set K is chosen as the optimal system design.

Discussion and Results

For the generic ESL system we are analyzing, the current readiness levels of its components and integration links are shown in Table 1. When reviewing the SRL for this system in its current state, the calculations yielded an SRL of 0.33. Referring to Figure 2, this value indicates that this system should be in *Phase A: Concept & Technology Development*.

Table 1: Current Readiness Levels

Technology			TRL
Technology 1	Air Revitalization		5
Technology 2	Crew Habitat		4
Technology 3	Water Processing		5
Technology 4	Waste Processing		4
Technology 5	Biomass Production		5
Technology 6	Food Processing		6
Integration	**IRL**	**Integration**	**IRL**
1,2	4	2,6	4
1,5	5	3,4	4
2,3	4	3,5	5
2,4	4	4,6	6
2,5	4	5,6	5

For the system used in this example, Tables 2 and 3 present the ESM of each component (technology or integration) at different maturity levels. For example, to mature Technology 1 from TRL of 1 to 9, its ESM can rise from 2,743 to 3,234 kgs. In order to fully mature all the technologies and integration elements, the ESL is allowed a maximum ESM of 44,876 without any amount budgeted for the usual management allowance.

Table 2: Cumulative ESM for Technology Elements against TRL (current TRLs in bold)

TRL	Technology					
	1	2	3	4	5	6
1	2743	2302	3350	1302	2926	17139
2	2835	2551	3489	1385	3074	18499
3	2986	2633	3765	1389	3273	19778

4	3058	**2767**	3897	**1462**	3356	19864
5	**3131**	2836	**3926**	1498	**3476**	20466
6	3212	2873	4004	1510	3526	**20988**
7	3230	2898	4044	1521	3562	21357
8	3233	2907	4096	1536	3580	21521
9	3234	2911	4111	1538	3597	21610

Table 3: Cumulative ESM for Integration Elements against IRL (current IRLs in bold)

IRL	Integration				
	1,2	**1,5**	**2,3**	**2,4**	**2,5**
1	624	963	1352	371	689
2	679	1017	1477	395	701
3	693	1088	1514	417	729
4	**729**	1090	**1540**	**431**	**744**
5	749	**1092**	1565	438	763
6	761	1116	1581	441	773
7	770	1130	1597	442	778
8	776	1136	1600	446	784
9	779	1144	1601	448	787
IRL	**Integration**				
	2,6	**3,4**	**3,5**	**4,6**	**5,6**
1	757	703	241	279	543
2	846	765	260	294	547
3	896	805	276	296	585
4	**943**	**847**	279	300	589
5	956	881	**290**	302	**604**
6	972	901	293	**303**	608
7	973	905	294	308	612
8	978	908	297	310	613
9	979	914	299	312	614

To further explain the model, we describe a situation where, for example, the program manager wants to show the customer, in this case the Constellation Program, to which maturity level or development stage he can take the ELS system if he is given various ESM allowances. In order to answer this, the PSDA optimization model calculated the maximum SRL values when 20%, 40%, 60%, 80% and all of the ESM allowance is allocated. The results are shown in Table 4. For example, when the ESM is allowed to increase from 43,273 (current value) to 43,901 (40% of total increase allowance), the SRL can be increased from 0.33 to 0.76. This takes the ELS system from *Phase A* to position where it would either have transition or soon transition from *Phase B: Preliminary Design & Technology Completion* to *Phase C: Final Design & Fabrication*.

In addition, the development plan which can achieve the SRL value of 0.76 when 40% of the ESM is allocated also shows that the subsystems which are based on each technology element reach their respective maturity levels as shown in Table 4. It shows that of the six subsystems, three are ahead ($SRL_{1,4,6}$), two are slightly behind ($SRL_{2,5}$) and one is close to the same level (SRL_3) as that of the whole system. This insight can become useful when the maturity levels are associated with systems engineering activities; hence, the spectrum of SRL_i's can indicate levels of variation in the systems engineering activities which are needed to mature the entire system.

Table 4: Best Solution for ESM Increase Allowance

Case	SRL_1	SRL_2	SRL_3	SRL_4
Current	0.35	0.28	0.31	0.33
20%	0.50	0.46	0.47	0.56
40%	0.81	0.69	0.75	0.79
60%	0.96	0.78	0.89	0.81
80%	1.00	0.90	0.97	0.92
100%	1.00	1.00	1.00	1.00
Case	SRL_5	SRL_6	**SRL**	**ESM**
Current	0.35	0.37	0.33	43273
20%	0.50	0.68	0.53	43579
40%	0.68	0.83	0.76	43901
60%	0.85	0.81	0.85	44221
80%	0.93	0.86	0.93	44249

100%	1.00	1.00	1.00	44876

Conclusions

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Biography

Weiping Tan received his B.E. with first class honor in 2006 in Automation from Beijing Institute of Technology, and received his M.E. in Engineering Management from Stevens Institute of Technology in 2009. He is currently pursuing his Ph.D. in Engineering Management at Stevens Institute of Technology in the School of Systems and Enterprises. His research interest is system maturity assessment. He was elected to Epsilon Mu Eta – the Engineering Management Honor Society, is the V.P. for the INCOSE Stevens Student Chapter, and received the Brian Mar Best Student Paper Award at the 2009 INCOSE International Symposium.

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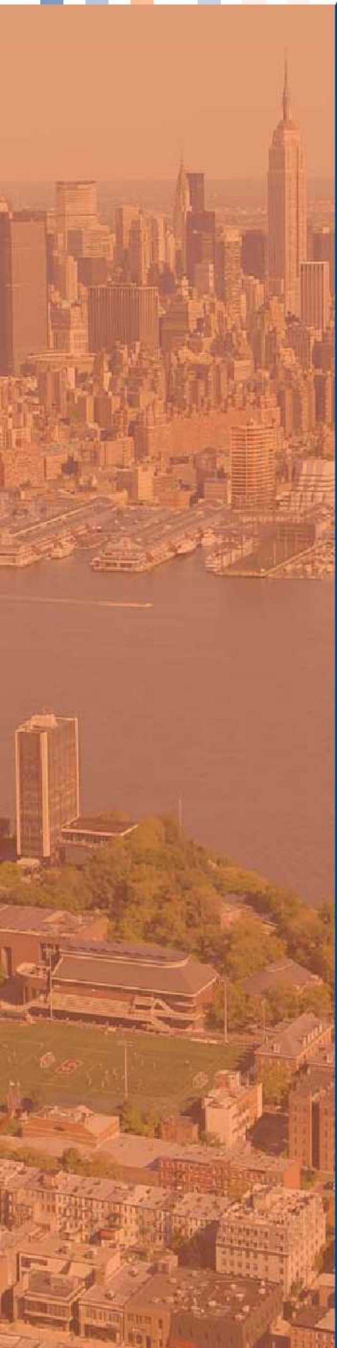

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3. The paper satisfactorily explains what was done.
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