Available online at www.sciencedirect.com
ScienceDirect
Procedia Computer Science 28 (2014) 340 – 346
Procedia
Computer Science

Conference on Systems Engineering Research (CSER 2014)

Eds.: Azad M. Madni, University of Southern California; Barry Boehm, University of Southern California;
Michael Sievers, Jet Propulsion Laboratory; Marilee Wheaton, The Aerospace Corporation
Redondo Beach, CA, March 21-22, 2014

A systems engineering approach to quantitative comparison of molecular instruments for use on the International Space Station

Kimberly Lineberger[a]*, Jennifer Levitt[b], David J. Smith[c], Troy Van Nguyen[d], Adrian M. Peter[e]

[a,d,e]*Florida Institute of Technology, 150 West University Blvd, Melbourne, FL 32901, USA*
[b,c]*NASA, Kennedy Space Center, FL 32899, USA*

Abstract

The presence of microorganisms on the International Space Station (ISS) poses a threat to the health and safety of the ISS crew. Currently the ISS utilizes culture-based methods to detect and identify microorganisms. These methods are out dated and time-consuming. Molecular methods can deliver accurate results and require less processing time. This article details an approach to determine which molecular methods instrument most closely meets the Microbial Monitoring System (MMS) requirements for use on the ISS. We utilize the decision-theoretic Analytical Hierarchy Process and Quality Function Deployment while aligning the systems requirements vs. instrument capabilities in a Pugh Matrix to perform a quantitative assessment of six candidate systems, with the analysis yielding a single recommended instrument for use on the ISS. We demonstrate our techniques to be very effective for selection of the best instrument—the recommended system is currently under consideration for use on the ISS.

Selection and peer-review under responsibility of the University of Southern California.

Keywords: Quality Function Deployment; QFD; Analytical Hierarchy Process; AHP; Pugh Matrix: Microbial Monitoring; qPCR;

---

* Kimberly Lineberger. Tel.: 404-421-8920.
E-mail address: klineberger2012@my.fit.edu

Selection and peer-review under responsibility of the University of Southern California.
doi:10.1016/j.procs.2014.03.042

1. Introduction

The presence of microorganisms on the International Space Station (ISS) poses a threat to the health and safety of the ISS crew. Microorganisms may infect crew members or damage Advanced Life Support Systems[1]. The ability to quickly detect and identify potentially harmful microbes on the ISS is therefore a high priority.

Currently, the ISS utilizes Microbial Analysis Packet (MAP) to identify microbes. This technique is culture-based, which presents several problems. First, researchers estimate that only 1% of known bacteria and archaea can be successfully grown in cultures[2]. Therefore, MAP is limited in the number of microbes it is able to identify. Second, the process of culturing necessitates the growth of colonies of microbes, some of which may be harmful. This presents a biohazard that may be difficult to dispose of. Finally, culturing is time-consuming. Cultures must be incubated for two days before a visual inspection can be performed. The results of the inspection must be emailed to ground microbiology labs for evaluation, introducing a communication delay. Crew members could be exposed to harmful microbes for days before they can be identified and treated. Because of these limitations, the ISS needs a more rapid means of microbial detection.

The most viable alternatives that mitigate many of the drawbacks of MAP are molecular techniques. Molecular methods can deliver results in hours, not days and allow for customizable targets. These methods are capable of identifying more types of microorganisms because they detect molecules within cellular structures.

Several systems are available which use molecular methods to identify microorganisms. Oubre, et al.[1] identified three platforms capable of performing quantitative Polymerase Chain Reaction (qPCR) as possible alternatives for culture-based methods. The qPCR technique examines nucleotides to identify microorganisms. Additionally, Morris et al.[3] developed and tested a system that uses various assays to detect the presence of molecules within the cell walls to identify microorganisms as a possible replacement for MAP.

This paper presents a systems engineering framework for evaluating Commercial Off the Shelf (COTS) microbial monitoring systems for use on the ISS. Voice of the Customer analysis has been used successfully in the Ground System Development and Operation Program at NASA Kennedy Space Center to evaluate design alternatives. This approach provides the opportunity to evaluate microbial monitoring systems and facilitate communication of needs and requirements of the ISS. We begin by defining customer requirements and critical attributes for the systems under consideration. We use Analytical Hierarchy Process (AHP) and Quality Function Deployment (QFD) to determine which attributes most heavily influence the selection process and evaluate each system against the requirements in a Pugh Matrix. This analysis yields a single recommended system for use.

The next section provides a brief discussion on the most relevant research to our present approach. This is followed by a detailed discussion of how systems analysis tools can be applied to the selection of the optimal microbial monitoring technique. Next, we provide experimental results that validate our approach, and finally, conclude with a brief discussion of our findings and possible extensions for the future.

Nomenclature

ISS	International Space Station
qPCR	quantitative Polymerase Chain Reaction
COTS	Commercial off the Shelf
QFD	Quality Function Deployment
AHP	Analytical Hierarchy Process
VOC	Voice of the Customer
CCR	Critical Customer Requirement

2. Relevant Work

As briefly discussed in the introduction, Oubre et al.[1] performed a proof-of-concept to confirm qPCR as a possible replacement for culture-based methods. The paper identified two possible commercial qPCR units to use on the ISS, which we have included in our analysis. Additionally, the paper defined some preliminary requirements the system should meet.

Quality Function Deployment was adopted as a decision-making technique by Western cultures in the 1980's[4]. It is a technique that measures the relationships between customer requirements and design specifications. Customer requirements may often be vague, such as "safe" or "easy to use", whereas design specifications are measureable system characteristics. Mehrjerdi[5] describes QFD as "a systematic approach enabling users to include customers' voices in the product planning and design phases." QFD takes into account both the customer's requirements and design requirements to maximize customer satisfaction. Analytical Hierarchy Process is another useful decision-making tool developed by Thomas Saaty[6]. AHP uses pairwise comparisons to evaluate the relative priority of multiple criteria. These comparisons result in a hierarchy of criteria to be used in evaluation of decision alternatives.

Bhattacharya et al.[7] developed an integrated model combining AHP and QFD for selecting industrial robots. This paper proposed a model for selection of robot or robotic systems from a customer requirements perspective. The approach computed the degree of relative importance for customer requirements through AHP and used the QFD transformation, relative importance of customer requirements, and normalized importance of each technical requirement to construct the robot selection model. An overall score for each robot was computed for the decision-maker to select the best robot based upon multiple criteria. This paper uses a similar approach to compute the relative importance of customer requirements and transform the customer requirements and desired system attributes into a meaningful score to make a system selection. Similarly, Tidwell and Sutterfield[8] veered from the traditional applications of QFD and applied it to supplier selection of toothpaste packaging. They used two iterations of the House of Quality Matrix to translate packaging characteristics into qualified suppliers. They found this method facilitated communication between stakeholders and led to rapid identification of qualified suppliers. Similarly, we apply QFD to determine the most important system characteristics and use these results to evaluate candidate systems in a Pugh Matrix. Cervone[9] described the benefits of Pugh Matrix Analysis (PMA) to make decisions that involve multiple dimensions and factors. He noted PMA is especially useful when "non-technological" issues are to be considered in the decision.

3. Methods

This section details an approach for using system analysis tools to select the optimal microbial monitoring technique. Our method relies on AHP to prioritize customer requirements and applies QFD to transform customer requirements into desired system attributes. Finally, we align the candidate systems against desired attributes in a Pugh Matrix to calculate an overall system score on which we base our recommendation.

The following molecular instruments are considered in this analysis:

- iC-System™, manufactured by iCubate
- Apollo, manufactured by Biocartis
- SmartCycler®, manufactured by Cepheid
- RAZOR EX®, manufactured by Idaho Technologies, Inc.
- Lab-On-A-Chip Application Development Portable Test System (LOCAD-PTS), manufactured by Charles River Laboratories
- Microbial Analysis Packet (MAP, baseline system), manufactured by IDEXX, American Flouorseal, and Moltox

The first step to perform this analysis was to gather the "Voice of the Customer". This step relied heavily on the use of affinity diagrams. Team members from multiple NASA centers listed several criteria a system should meet. These criteria were grouped together in affinity diagrams, and the main idea of each group was defined to be the top- level Voice of the Customer (VOC) input.

	Safety	Performance	Operability	Functionality	Manufacturability	Sum of Normalized Ratings	Weight
Safety	1.00	3.00	5.00	5.00	9.00	2.42	**0.48**
Performance	0.33	1.00	1.00	5.00	9.00	1.15	**0.23**
Operability	0.20	1.00	1.00	3.00	7.00	0.87	**0.17**
Functionality	0.20	0.20	0.33	1.00	5.00	0.42	**0.08**
Manufacturability	0.11	0.11	0.14	0.20	1.00	0.15	**0.03**
Column Total	1.84	5.31	7.48	14.20	31.00		

Figure 1. Voice of the Customer analysis. Rankings from the ISS Program Office were entered into an AHP Matrix in order to calculate weights and determine the relative importance of customer requirements.

The VOC attributes are defined as follows:

- Safety: system ensures safety of flight and ISS crew, ground personnel, flight vehicles, public, and environment
- Operability: system is easy to use
- Functionality: system is capable of performing required tasks
- Performance: system is able to accurately identify target microbes within a sample
- Manufacturability: system is able to be modified for space flight

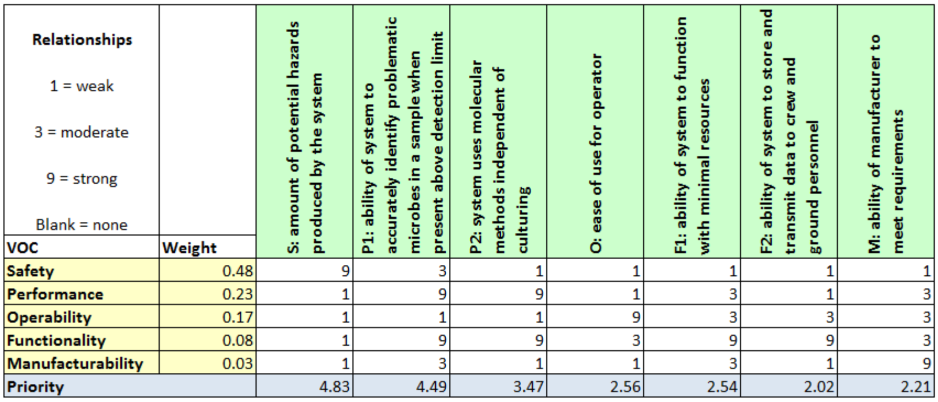
Once the VOC attributes were defined, Analytical Hierarchy Process was employed to assign relative priorities to each VOC requirements and calculate appropriate weights. The VOC categories were placed in an AHP matrix, and contacts at the ISS Program Office ranked each VOC elements in order of importance using a 1 to 9 scale described in Table 1. Figure 1 illustrates the AHP Matrix. The matrix facilitates pairwise comparisons of each customer requirement. Once each cell is filled in, the matrix columns are summed. The cells are then normalized by calculating the quotient of the cell entry and its corresponding column sum. A normalized row mean is calculated for each row, resulting in a weight for each customer requirement.

Table1. AHP Ranking Matrix Scale

Scale	
1	Equally Important
3	Somewhat More Important
5	Moderately More Important
7	Much More Important
9	Overwhelmingly More Important

Table 2. Pugh Matrix System Scores

Score	
(+++)	Very Much Better
(++)	Much Better
(+)	Better
(s)	Same
(-)	Worse
(--)	Much Worse
(---)	Very Much Worse



Relationships 1 = weak 3 = moderate 9 = strong Blank = none		**S: amount of potential hazards produced by the system**	**P1: ability of system to accurately identify problematic microbes in a sample when present above detection limit**	**P2: system uses molecular methods independent of culturing**	**O: ease of use for operator**	**F1: ability of system to function with minimal resources**	**F2: ability of system to store and transmit data to crew and ground personnel**	**M: ability of manufacturer to meet requirements**
VOC	**Weight**							
Safety	0.48	9	3	1	1	1	1	1
Performance	0.23	1	9	9	1	3	1	3
Operability	0.17	1	1	1	9	3	3	3
Functionality	0.08	1	9	9	3	9	9	3
Manufacturability	0.03	1	3	1	1	3	1	9
Priority		4.83	4.49	3.47	2.56	2.54	2.02	2.21

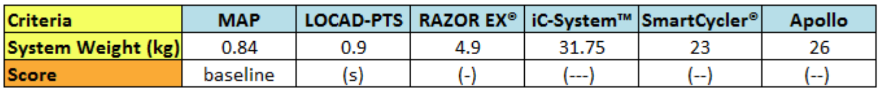
Figure 2. Customer requirements (VOC) and system attributes (CCRs) were evaluated in a QFD Matrix to calculate a priority score for each CCR.

Additionally, desirable system attributes were developed and defined to be the Critical Customer Requirement (CCR) inputs. Each CCR had individual fit criteria associated with it for data collection and scoring purposes. The CCRs are defined as follows:

- S: number of potential hazards produced by the system
- P1: system is able to accurately identify problematic microbes in a sample when present above detection limit
- P2: system uses molecular methods independent of culturing
- O: number of steps the operator performs
- F1: system is able to function with minimal resources
- F2: system is able to store and transmit data to crew and ground personnel
- M: manufacturer is able to make modifications to system

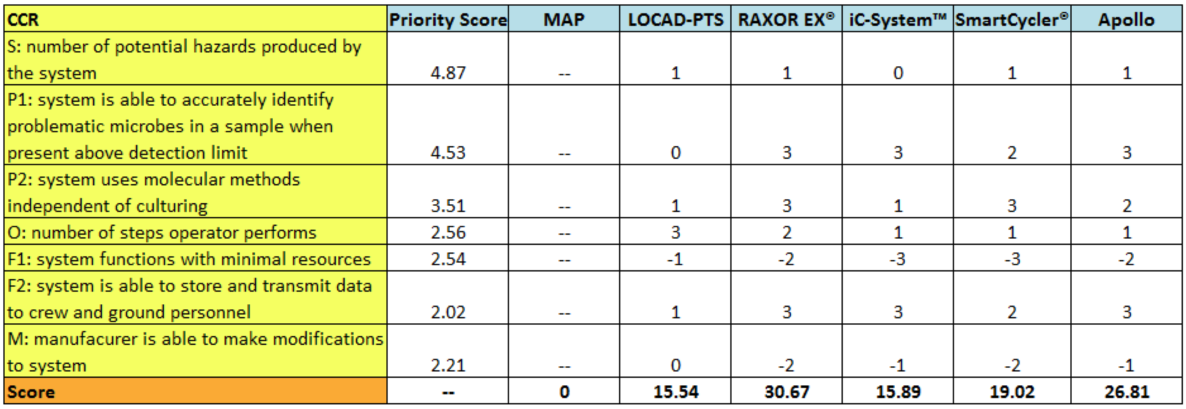
QFD was used to measure the relationships between each VOC and CCR and to calculate a priority score for each CCR. Figure 2 illustrates the QFD Matrix used to calculate these scores. We evaluated the relationship between each VOC and CCR according to the scale in Figure 2. These ratings were combined with the VOC weights in the QFD Matrix to calculate a priority score for each CCR. Data was collected for each system under each CCR using more specific fit criteria that contributed to a system score. Figure 3 illustrates the data collection for one criterion.

The systems were aligned in a Pugh Matrix with the CCRs and corresponding priority scores to be evaluated against the baseline MAP. For each CCR, the systems received a score to indicate how well it satisfied the requirement relative to the baseline. Table 2 explains the scale used to score each system. Each plus or minus score was converted into a scalar for the calculations. The CCR priority scores were multiplied by each system score, and the resulting products were summed for each system, yielding a total system score. The system with the highest total score was recommended for use on the ISS.



Criteria	**MAP**	**LOCAD-PTS**	**RAZOR EX®**	**iC-System™**	**SmartCycler®**	**Apollo**
System Weight (kg)	0.84	0.9	4.9	31.75	23	26
Score	baseline	(s)	(-)	(---)	(--)	(--)

Figure 3. Data collection and system scoring for a single fit criterion of the CCR F1.



CCR	Priority Score	MAP	LOCAD-PTS	RAXOR EX®	iC-System™	SmartCycler®	Apollo
S: number of potential hazards produced by the system	4.87	--	1	1	0	1	1
P1: system is able to accurately identify problematic microbes in a sample when present above detection limit	4.53	--	0	3	3	2	3
P2: system uses molecular methods independent of culturing	3.51	--	1	3	1	3	2
O: number of steps operator performs	2.56	--	3	2	1	1	1
F1: system functions with minimal resources	2.54	--	-1	-2	-3	-3	-2
F2: system is able to store and transmit data to crew and ground personnel	2.02	--	1	3	3	2	3
M: manufacurer is able to make modifications to system	2.21	--	0	-2	-1	-2	-1
Score	**--**	**0**	**15.54**	**30.67**	**15.89**	**19.02**	**26.81**

Figure 4. Systems were aligned in a Pugh Matrix and scored for each CCR. The Pugh Matrix analysis resulted in an overall system score on which the recommendation to the ISS Program Office was based.

4. Results

Our systems analysis approach to evaluating microbial monitoring techniques provides a quantitative mechanism by which to incorporate customer requirements, assuring that the unique operating conditions of the ISS influence the selection. Table 3 shows the corresponding weights for each VOC input as calculated in the AHP Matrix. Figure 4 details the systems aligned with the CCRs and corresponding scores and in the Pugh Matrix. Because the systems are scored relative to the baseline, MAP receives a score of 0 by definition. A positive score indicates a system satisfies the requirement better than the baseline. A negative score indicates the system is worse than the baseline for satisfying a requirement. The positive and negative scores are summed to yield a total system score. The highest score possible was 66.72. All systems received positive scores, indicating they would all outperform the baseline system MAP. However, the RAZOR EX® system received the highest system score of 30.67. The Apollo system received the second highest score with 26.81. Cepheid's SmartCycler® received a score of 19.2. The iC-System™ and LOCAD-PTS scored lowest with 15.89 and 15.54 respectively. Based on these scores, RAZOR EX® was recommended to replace MAP on the ISS.

The Pugh Matrix Analysis clearly breaks down the areas in which systems outperform one another. Moreover, it provides a meaningful value to each system, allowing a more objective decision to be made. While there is some subjectivity in the ranking system because it relies on decision makers' preferences of criteria, this process ensures decision makers do not overlook key properties when selecting a system.

5. Conclusions

This paper presents a framework for employing Systems Engineering decision techniques to select the best replacement microbial monitoring system for use on the ISS. We employed AHP to prioritize customer requirements and applied QFD to transform customer requirements into critical system attributes. Each system was evaluated against these criteria in a Pugh Matrix and awarded a relative score for its performance compared to the baseline system. The Pugh Matrix analysis yielded a total system score on which the system recommendation was based.

All systems and scores were presented to Microbial Monitoring System (MMS) teams from multiple NASA centers. These results facilitated discussions about a replacement system and allowed for the quick selection of a system. The recommended RAZOR EX® system is currently under consideration for use on the ISS.

References

1. Oubre, Cherie M., Birmele Michele N., Castro, Victoria A., Venkateswaran, Kasthuri J., Vaishampayan, Parag A., Jones, Kathy U., Shngal, Adesh, Johnston, Angela S., Roman, Monserrate C., Ozbolt, Tamara A., Jett, Daniel X., Roberts, Michael S., Ott, Mark C. (July 2013). *Microbial Monitoring of Common Opportunistic Pathogens by Comparing Multiple Real-Time PCR Platforms for Potential Space Applications*. Unpublished paper presented at the 43rd International Conference on Environmental Systems, Vail, CO.
2. Freeman, Scott. *Biological Sciences, 4th Edition*. San Francisco, CA: Benjamin Cummings; 2010.
3. Morris, Heather C., Damon, Michael, Maule, Jake, Monaco, Lisa A., Wainwright, Norm. Rapid Culture-Independent Microbial Analysis Aboard the International Space Station (ISS) Stage Two: Quantifying Three Microbial Biomarkers. *Astrobiology* 2012; **12:**830 – 840.
4. Franceschini, Fiorenzo. *Advanced Quality Function Deployment.* Boca Raton, FL: CRC Press LLC; 2001.
5. Mehrjerdi, Yahia Zare. Quality function deployment and its extensions. *International Journal of Quality and Reliability Management* 2010; **27**:616-640
6. Saaty, Thomas L. *Mathematical Principles of Decision Making.* Pittsburgh, PA: RWS Publications; 2010.
7. Bhattacharya, Arjit, Sarkar, Bijan, Mukherjee, Sanat Kumar. Integrating AHP with QFD for robot selection under requirement perspective. *International Journal of Production Research* 2005; **43:** 3671- 3685.
8. Tidwell, Angela, Sutterfield, Scott J. Supplier selection using QFD: a consumer products case study. *International Journal of Quality & Reliability Management* 2005; **29:**284-294.
9. Cervone, Frank H. (2009). Applied digital library project management: Using Pugh matrix analysis in complex decision-making situations. *OCLC Systems & Services: International Digital Library Perspectives* 2009; **25:**228-232.