EVALUATION OF ROBOTICS IN THE APPLICATION OF PUF ROOFING

Dean T. Kashiwagi PhD PE, William C. Moor PhD, J. Pablo Nuno PhD
Department of Industrial Engineering
College of Engineering
Arizona State University
Tempe, Arizona 85287-5906

William W. Badger PhD PE
Department of Construction
College Of Engineering
Arizona State University
Tempe, Arizona 85287-0204

ABSTRACT

The purpose of this paper is twofold: 1) to introduce a new methodology to evaluate facility systems and the application of robotics in facility management operations; 2) to use the methodology to analyze the viability of the application of robotics in installing polyurethane foam (PUF) roof systems.

The "Romer" is a robot that installs PUF roofs. Its development, operational characteristics, and advantages and disadvantages are discussed. The impact of the technology is discussed in terms of a relative "fuzzy number" and present cost or profit. Utilizing the "Romer" robot in a test case is the best option for the constructor and the owner in terms of present cost, profit, and performance. This allows both the constructor and the facility owner to benefit from the implementation of the robot. The impact of the technology is specific to the test case and is dictated by alternative options to meet the facility system requirement.

INTRODUCTION

The construction industry is feeling the effects of the new "worldwide competition." As the marketplace becomes more competitive, construction practices must be optimized for constructors to remain profitable. The construction industry is one of the last industries to implement robotics. Constructors require a process to determine if the robotics will:

1. Make constructors more competitive.
2. Add value to the facility system.

This paper utilizes "fuzzy logic" to analyze these two requirements. The definition of performance is first derived from a basic understanding of industry structure. The performance factors are then quantified in relative terms. A performance based procurement process utilizing the "Displaced Ideal Model" is then discussed. The "value added" performance of the robot is then determined through engineering analysis, and its impact measured in terms of relative present worth.

STRUCTURE OF THE ROOFING

The determination of performance factors is key to the determination of a facility system's value. Due to the different methods and physical characteristics of competing facility systems, performance factors become an attractive method of defining facility system performance. This is emphasized by Porter[13] who defines several requirements for structural stability of an industry. They include:

1. The ability of industry participants to keep a fair share of the "value added" worth of the finished product.
2. The ability to differentiate the product by its value.

3. The industry's ability to assist the buyer in perceiving the "value added" nature of the product.
4. Industry entry/exit barriers that prevent newcomers from eroding product differentiation, profits, and inundating the market.

Kashiwagi has shown that if this definition is applied, the segment of the construction industry that manufactures and installs facility systems is unstable[10]. A methodology has been developed to determine the "value added" nature of the facility systems, differentiate systems by its performance, stabilize the industry and increase the value of the facility systems, and determine the "value added" nature of new technology such as robotics. With the advances in computer technology and the development of artificial intelligent or "fuzzy logic" models and the implementation of management of information to make decisions, facility system performance can now be determined by performance data. The facility system selected to test the methodology is the roofing or waterproofing system of a facility.

PERFORMANCE FACTORS

Instead of attempting to define the minimum performance standards through rigorous testing of materials and system samples, it is now possible to "fingerprint" a contractor to provide the quality of roof system performance provided and to competitively award the roofing contract to the best performing system utilizing the "Displaced Ideal Model" (DIM). The design of this methodology requires the collection of data, the creation of a new design/procurement methodology, and the determination of performance factors. Kashiwagi has been collecting data on roofs since 1983[7,8,9]. He determined that the performance of roof systems is determined by the facility owner's requirements and includes a combination of the following:

1. The installation cost of the roof system.
2. The maximum performance period of the roof system. constructors in the same environmental conditions.
3. The proven performance period of the roof system installed by the constructor bidding the project.
4. The percentage of roofs not receiving any maintenance.
5. The equivalent uniform annual cost (EUAC) of the roof system.
6. The contractor response time away from the facility.
7. Customer satisfaction.
8. The percentage of roofs without any leaks.
9. The physical condition of the roof.
10. The environmental and physical specifications of the roof.
11. The number of roofs not requiring more than one percent repair.
12. The percentage of roofs that leaked but were repaired.

DESIGN/PROCUREMENT PROCESS

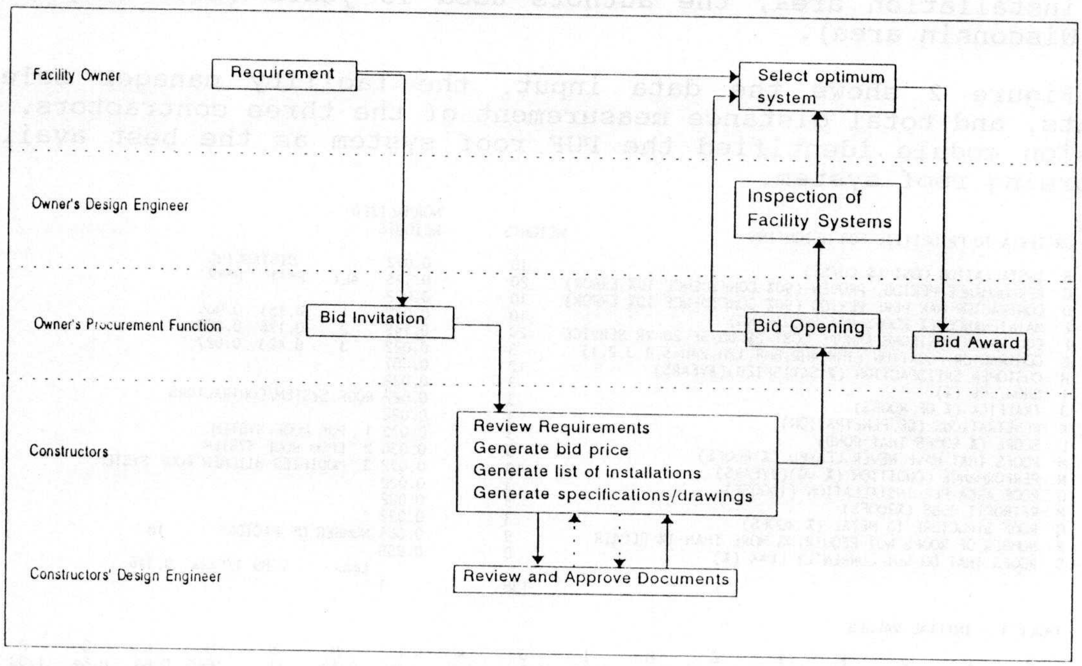
A prototype system was designed for the procurement of roofing systems (Figure 1). To start the process, a facility manager generates a roofing system requirement (number of square feet to be reroofed). The invitation for bids requests a roof system name, price, and a list and access to 100 previous installations of that system. The bid opening is followed by the data collection of previous system performances. The objective of the bid opening is to verify if all the interested constructors have met the requirements of the invitation to bid. The data for each constructor is then collected and compiled. The compiled data and the proposed bid price becomes the bid submittal for the contractor. The procurement decision model utilizes the "Displaced

Ideal model" as discussed by Zeleny (1982). The model determines the performance of a system by:

1. Creating an imaginary "optimal" system performance by selecting the optimal value of each performance criterion from the available alternative systems.

2. Determining a relative distance of each alternative system from the optimum. This distance is affected by the "amount of information" of each performance criterion which is calculated using an entropy relationship and by the facility owner's facility requirements.

3. The alternative that is closest to the imaginary "optimum" system performance is the best performing roof system.



Functional Diagram of Performance Based Design/Procurement Process

Figure 1

The objective of the decision module is to identify the system performance of all the alternatives and the "best available" system. "Fuzzy logic" fits well because it is very difficult to specify an "absolute" roof system performance requirement. The approach of the performance based system is to determine which system is the "best" performing system. The same methodology can be utilized to evaluate the "added worth" of new technology.

TEST CASE OF PERFORMANCE BASED DESIGN/PROCUREMENT PROCESS

A facility manager for a national company was contacted in the Midwest region of the United States to verify and validate the new performance based procurement system. Three contractors proposed different alternative roofing systems. The inspection of roofs and collection of data for the three contractors provided the following results:

1. Contractor #2 had the best maintenance and customer followup record.
2. Contractor #1 and #2 roofs were very close in the lack of physical deterioration in their systems, maintenance required by the user, and customer satisfaction.
3. Contractor #3 differed in quality of work from the other contractors. He did not generate an 100 previous roof jobs. Even though the roofing system he installed showed very little deterioration, 7 out of 10 (83%) of his roofs that were inspected leaked and only one was repaired. Only 33% of his customers were satisfied with the contractor/roof systems performance.
4. Contractor #2 had older roofs than contractor 1, but the roof system installed by contractor #1 had a longer documented performance history. For the proven performance of PUF in the installation area, the authors used 15 years (data sample from Wisconsin area).

Figure 2 shows the data input, the facility manager selected weights, and total distance measurement of the three contractors. The decision module identified the PUF roof system as the best available performing roof system.

ORDER OF WEIGHTS		CRITERIA TO PRIORITIZE FOR WEIGHTING	WEIGHTS	NORMALIZED WEIGHTS
3	B	INSTALLATION COST ($.00/SF)	10	0.072
1	C	PERFORMANCE PERIOD, PROVEN (90% CONFIDENCE 10% ERROR)	20	0.145
3	D	CONTRACTOR MAX PERF PERIOD (90% CONFIDENCE 10% ERROR)	10	0.072
3	E	MAINTENANCE (% ROOFS NOT REQUIRING)	10	0.072
1	F	EQUIVALENT UNIFORM ANNUAL COST ($.00/SF 20 YR SERVICE	20	0.145
7	G	CONTRACTOR LOCATION (1HR,4HR,8HR,12H,24H:5,4,3,2,1)	3	0.022
2	H	CUSTOMER SATISFACTION (# SATISFIED)(#YEARS)	12	0.087
7	I	SNOW/ICE (%)	3	0.022
7	J	TRAFFICK (% OF ROOFS)	3	0.022
7	K	PENETRATIONS (SF/PENETRATION)	3	0.022
7	L	SLOPE (% ROOFS THAT POND)	3	0.022
6	M	ROOFS THAT HAVE NEVER LEAKED (% ROOFS)	5	0.036
3	N	PERFORMANCE CONDITION (% VG)(#YEARS)	10	0.072
7	O	ROOF AREA PER INSTALLATION (1000SF)	3	0.022
7	P	RETROFIT JOBS (%ROOFS)	3	0.022
7	Q	ROOF STRUCTURE IS METAL (% ROOFS)	3	0.022
4	R	NUMBER OF ROOFS NOT REQUIRING MORE THAN 1% REPAIR	9	0.065
5	S	ROOFS THAT DO NOT CURRENTLY LEAK (%)	8	0.058
			138	1

DISTANCING

ALT	P**1	P**2
1	0.151	0.005
2	0.176	0.008
3	0.423	0.027

ROOF SYSTEM/CONTRACTORS

1 PUF ROOF SYSTEM
2 EPDM ROOF SYSTEM
3 MODIFIED BITUMEN ROOF SYSTEM

NUMBER OF FACTORS 18

Emax 2.89 1/Emax 0.346

TABLE 1 - INITIAL VALUES

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	($2.31)	15.0	3	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	4665	0.88	0.54	1.00	0.90
2	($2.74)	7.0	7	0.95	($0.51)	3.00	137	1.00	0.50	-737	0.78	0.55	60	16997	0.52	0.90	1.00	1.00
3	($1.89)	5.0	5	0.75	($0.82)	3.00	50	1.00	0.75	-444	0.70	0.30	33	6442	0.70	0.40	1.00	0.40
BEST VALUES	($1.89)	15.0	7	0.95	($0.49)	4.00	137	1.00	0.75	-444	0.80	0.78	71	16997	0.88	0.90	1.00	1.00

Ideal Displaced Model Inputs For Performance Calculations
Figure 2

EVALUATION OF NEW TECHNOLOGY

The performance based process was then utilized to evaluate the "value added" worth of new technology. The technology selected is the robotic application of PUF. In 1979, the Chicago Bridge and Iron Company, developed the first robotic PUF spray applicator to automate the spraying of PUF on petroleum storage tanks. The robot was designed and constructed to imitate an optimum PUF hand sprayer. The first prototype machine was operationally tested in 1980, and by 1987, modifications and technological advancements made the robot operationally and economically feasible. By 1990, ten contractors were operating the robots. By the end of 1990, 5 million square feet of PUF roofing has been installed using the robot. In August 1990, the robots were timed and production documented in an operational test at a 900,000 SF automobile manufacturing plant in Detroit, Michigan. The performance data of the robot was compiled in Table 1. The robot achieves the following purposes:

1. Enables the PUF to be installed at the full thickness in one pass, reducing delamination and blistering.
2. Allows the faster installations.
3. Minimizes the failure at pass lines.
4. Allows the mechanical sloping of roofs.

Table 1
Robot Performance Measures

1.	Percent time in operation:	79%
2.	Average speed:	8 FT/MIN
3.	Output/HR:	2247 SF/HR
4.	Output/10 HR day:	22,470 SF
6.	Yield/1000 LBs PUF:	3443 SF
7.	Yield percentage:	96%
8.	Savings/SF (material cost of PUF):	$.17
9.	Payback on equipment due to saved PUF material spraying 1.5 IN (SF):	142,857 SF
10.	Average depth of PUF (19 readings):	1.54 IN
11.	Uploading/Downloading Time on 50 foot high roof with a motorized lift:	10 minutes

The added worth of the robotic application was determined by the performance based system in terms of impact on the optimum available roof system (Kashiwagi, 1991). Since the performance requirements are based on the user's strategic plan for the facility, the added worth of the robot application will differ from installation to installation, and from applicator to applicator. As the analysis of the robot application stated, the first cost of the robot application does not increase if the size of the roof is over 142,857 SF. Therefore, the added worth of the robot application can be measured in terms of:

1. Extending the service period of the constructor installed system from the proven service period to a conservative 20 year period. This is justified due to the proven performance period of 20 years by manual installation which is less effective than robotic application. Therefore, the assumption is that with robotic application, the variability between constructors is drastically reduced, and the maximum proven service period becomes the same between constructors who robotically install the PUF roof system.

2. Eliminating the need of layering the PUF to prevent ponding on the roof. Layering is done in thin lifts and is a source of blistering and shortening of the service period of the roof system. This will further enhance the service period of the PUF roof system.

3. Decreasing the requirement of repairs and the area of deterioration due to the elimination of the source of delamination and blistering.

4. Increasing the constructor capability of roof surface size with the robot to a minimum of one and one half times the current proven capability. The capability to do a large roof is primarily connected with the spraying speed of the constructor. An average of 15,500 SF for a ten hour day (including one hour break for lunch) is used for the rate by manual application from one of the most effective constructors. The robot can produce approximately 22,500 SF per 10 hour day if run for 90% of the time.

5. Reducing the cost of the roof system. The break even point for the robot is spraying 142,857 SF of 1.5 inches of PUF. After the robot

is utilized for no cost. The service life of a robot has not been determined. Maintenance costs are minimal, and the critical component is the spray gun which is not a part of the robot. If the labor cost and PUF material cost savings are calculated after the robot is paid off, the savings is $.21/SF.

A new constructor/roofing system (Constructor/system #4 in Figure 3) was added to the evaluation of roofing systems. The following changes are made to Constructor #1's performance line to create the new performance line:

1. Criteria D (Maximum proven performance period for constructor) 20 years.
2. Criteria O (Roof Area per installation) 4665 X 1.5 = 6997.5SF.

ORDER OF WEIGHTS		CRITERIA TO PRIORITIZE FOR WEIGHTING	WEIGHTS	NORMALIZED WEIGHTS
3	B	INSTALLATION COST ($.00/SF)	10	0.072
1	C	PERFORMANCE PERIOD, PROVEN (90% CONFIDENCE 10% ERROR)	20	0.145
3	D	CONTRACTOR MAX PERF PERIOD (90% CONFIDENCE 10% ERROR)	10	0.072
3	E	MAINTENANCE (% ROOFS NOT REQUIRING)	10	0.072
1	F	EQUIVALENT UNIFORM ANNUAL COST ($.00/SF 20 YR SERVICE)	20	0.145
7	G	CONTRACTOR LOCATION (1HR, 4HR, 8HR, 12H, 24H: 5, 4, 3, 2, 1)	3	0.022
2	H	CUSTOMER SATISFACTION (# SATISFIED)(#YEARS)	12	0.087
7	I	SNOW/ICE (%)	3	0.022
7	J	TRAFFICK (% OF ROOFS)	3	0.022
7	K	PENETRATIONS (SF/PENETRATION)	3	0.022
7	L	SLOPE (% ROOFS THAT POND)	3	0.022
6	M	ROOFS WITHOUT REPAIRED LEAKS DUE TO ROOF (% ROOFS)	5	0.036
3	N	PERFORMANCE CONDITION (% VG)(#YEARS)	10	0.072
7	O	ROOF AREA PER INSTALLATION (1000SF)	3	0.022
7	P	RETROFIT JOBS (%ROOFS)	3	0.022
7	Q	ROOF STRUCTURE IS METAL (% ROOFS)	3	0.022
4	R	NUMBER OF ROOFS NOT REQUIRING MORE THAN 1% REPAIR	9	0.065
5	S	ROOFS THAT HAVE NO LEAKS DUE TO ROOF (%)	8	0.058
			138	1

DISTANCING

ALT	P**1	P**2
1	0.209	0.008
2	0.240	0.013
3	0.470	0.032
4	0.107	0.003

ROOF SYSTEM/CONTRACTORS

1 PUF ROOF SYSTEM
2 EPDM ROOF SYSTEM
3 MODIFIED BITUMEN ROOF SYSTEM
4 ROBOT INSTALLED PUF ROOF SYSTEM

NUMBER OF FACTORS 18

TABLE 1 - INITIAL VALUES

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	($2.31)	15	3	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	4665	0.88	0.54	1.00	0.90
2	($2.74)	7	7	0.95	($0.51)	3.00	137	1.00	0.50	-737	0.78	0.55	60	16997	0.52	0.90	1.00	1.00
3	($1.89)	5	5	0.75	($0.82)	3.00	50	1.00	0.75	-444	0.70	0.30	33	6442	0.70	0.40	1.00	0.40
4	($2.31)	20	20	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	6998	0.88	0.54	1.00	0.90
BEST VALUE	($1.89)	20	20	0.95	($0.49)	4	137	1.00	0.75	-444	0.80	0.78	71.00	16997	0.88	0.90	1.00	1.00

Addition of the Robotic Application Line Item
Figure 3

Criteria N (Performance Condition) and Criteria R (% of Roofs Not Requiring Repair) were not changed because the PUF roof system constructor's performance concerning these criteria could not be improved by the utilization of the robot. A contractor with lower performance values would be benefited more by the robot. The robotic application technology is "value-added" technology when applied to this selection of the optimum available roof system whether considering the time period when the robot is being paid for by the savings in labor and PUF or after it is paid off. In Figure 3, the initial cost is not reduced to $2.10, but kept at $2.31. At this price, the robot is paid for after the installation of 142,857 SF of PUF roofing system. Figure 4 shows the results of adding an alternative of constructor #1 utilizing the robot after it has been paid off. The new alternative is the optimum available system by a comfortable margin. With the robot utilization, there is a clear gap between the robotic alternative and the hand installed PUF roof systems.

The utilization of the robot technology is beneficial to both the constructor and the facility user. It is the optimum available roof system for the user, and allows the constructor to move his initial cost between $2.10 and $5.03, and still be the installer of the optimal roof system (see Figure 5). The worth of technology will vary in different applications, and should be modeled into an alternative line item in the "value engineering" process for each installation.

ORDER OF WEIGHTS		CRITERIA TO PRIORITIZE FOR WEIGHTING	WEIGHTS	NORMALIZED WEIGHTS
3	B	INSTALLATION COST ($.00/SF)	10	0.072
1	C	PERFORMANCE PERIOD, PROVEN (90% CONFIDENCE 10% ERROR)	20	0.145
3	D	CONTRACTOR MAX PERF PERIOD (90% CONFIDENCE 10% ERROR)	10	0.072
3	E	MAINTENANCE (% ROOFS NOT REQUIRING)	10	0.072
1	F	EQUIVALENT UNIFORM ANNUAL COST ($.00/SF 20 YR SERVICE)	20	0.145
7	G	CONTRACTOR LOCATION (1HR,4HR,8HR,12H,24H:5,4,3,2,1)	3	0.022
2	H	CUSTOMER SATISFACTION (# SATISFIED)(#YEARS)	12	0.087
7	I	SNOW/ICE (%)	3	0.022
7	J	TRAFFICK (% OF ROOFS)	3	0.022
7	K	PENETRATIONS (SF/PENETRATION)	3	0.022
7	L	SLOPE (% ROOFS THAT POND)	3	0.022
6	M	ROOFS WITHOUT REPAIRED LEAKS DUE TO ROOF (% ROOFS)	5	0.036
3	N	PERFORMANCE CONDITION (% VG)(#YEARS)	10	0.072
7	O	ROOF AREA PER INSTALLATION (1000SF)	3	0.022
7	P	RETROFIT JOBS (%ROOFS)	3	0.022
7	Q	ROOF STRUCTURE IS METAL (% ROOFS)	3	0.022
4	R	NUMBER OF ROOFS NOT REQUIRING MORE THAN 1% REPAIR	9	0.065
5	S	ROOFS THAT HAVE NO LEAKS DUE TO ROOF (%)	8	0.058
			138	1

DISTANCING

ALT	P**1	P**2
1	0.209	0.008
2	0.240	0.013
3	0.470	0.032
4	0.099	0.003

ROOF SYSTEM/CONTRACTORS

1 PUF ROOF SYSTEM
2 EPDM ROOF SYSTEM
3 MODIFIED BITUMEN ROOF SYSTEM
4 ROBOT INSTALLED PUF ROOF SYSTEM

NUMBER OF FACTORS 18

TABLE 1 - INITIAL VALUES

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	($2.31)	15	3	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	4665	0.88	0.54	1.00	0.90
2	($2.74)	7	7	0.95	($0.51)	3.00	137	1.00	0.50	-737	0.78	0.55	60	16997	0.52	0.90	1.00	1.00
3	($1.89)	5	5	0.75	($0.82)	3.00	50	1.00	0.75	-444	0.70	0.30	33	6442	0.70	0.40	1.00	0.40
4	($2.10)	20	20	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	6998	0.88	0.54	1.00	0.90
BEST VALUE	($1.89)	20	20	0.95	($0.49)	4	137	1.00	0.75	-444	0.80	0.78	71.00	16997	0.88	0.90	1.00	1.00

Robotic Application After Robot is Paid Off
Figure 4

ORDER OF WEIGHIS		CRITERIA TO PRIORITIZE FOR WEIGHTING	WEIGHTS	NORMALIZED WEIGHTS
3	B	INSTALLATION COST ($.00/SF)	10	0.072
1	C	PERFORMANCE PERIOD, PROVEN (90% CONFIDENCE 10% ERROR)	20	0.145
3	D	CONTRACTOR MAX PERF PERIOD (90% CONFIDENCE 10% ERROR)	10	0.072
3	E	MAINTENANCE (% ROOFS NOT REQUIRING)	10	0.072
1	F	EQUIVALENT UNIFORM ANNUAL COST ($.00/SF 20 YR SERVICE)	20	0.145
7	G	CONTRACTOR LOCATION (1HR,4HR,8HR,12H,24H:5,4,3,2,1)	3	0.022
2	H	CUSTOMER SATISFACTION (# SATISFIED)(#YEARS)	12	0.087
7	I	SNOW/ICE (%)	3	0.022
7	J	TRAFFICK (% OF ROOFS)	3	0.022
7	K	PENETRATIONS (SF/PENETRATION)	3	0.022
7	L	SLOPE (% ROOFS THAT POND)	3	0.022
6	M	ROOFS WITHOUT REPAIRED LEAKS DUE TO ROOF (% ROOFS)	5	0.036
3	N	PERFORMANCE CONDITION (% VG)(#YEARS)	10	0.072
7	O	ROOF AREA PER INSTALLATION (1000SF)	3	0.022
7	P	RETROFIT JOBS (%ROOFS)	3	0.022
7	Q	ROOF STRUCTURE IS METAL (% ROOFS)	3	0.022
4	R	NUMBER OF ROOFS NOT REQUIRING MORE THAN 1% REPAIR	9	0.065
5	S	ROOFS THAT HAVE NO LEAKS DUE TO ROOF (%)	8	0.058
			138	1

DISTANCING

ALT	P**1	P**2
1	0.209	0.008
2	0.240	0.013
3	0.470	0.032
4	0.209	0.016

ROOF SYSTEM/CONTRACTORS

1 PUF ROOF SYSTEM
2 EPDM ROOF SYSTEM
3 MODIFIED BITUMEN ROOF SYSTEM
4 ROBOT INSTALLED PUF ROOF SYSTEM

NUMBER OF FACTORS 18

TABLE 1 - INITIAL VALUES

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	($2.31)	15	3	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	4665	0.88	0.54	1.00	0.90
2	($2.74)	7	7	0.95	($0.51)	3.00	137	1.00	0.50	-737	0.78	0.55	60	16997	0.52	0.90	1.00	1.00
3	($1.89)	5	5	0.75	($0.82)	3.00	50	1.00	0.75	-444	0.70	0.30	33	6442	0.70	0.40	1.00	0.40
4	($5.03)	20	20	0.92	($0.49)	4.00	67	1.00	0.29	-480	0.80	0.78	71	6998	0.88	0.54	1.00	0.90
BEST VALUE	($1.89)	20	20	0.95	($0.49)	4	137	1.00	0.75	-444	0.80	0.78	71.00	16997	0.88	0.90	1.00	1.00

Break-Even Installation Cost of Robotic Application
Figure 5

CONCLUSION

The implementation of the performance based design/procurement process by facility managers, and manufacturers and contractors of roof systems maximizes roof system performance. The philosophy provides a quick method to accurately access the "added worth" of new technology for each roofing application. The DIM which is used by the decision module does not require performance factors to be mutually or preferentially independent. Therefore the process can quickly identify the critical performance factors with minimal data collection and analysis effort. The process allows the determination of the "value added" worth of a technology of a specific facility system by considering all alternative facility systems. The process identified the PUF spraying robot as having tremendous "value added" worth, doubling the first cost worth from $2.31/SF to $5.03/SF.

ACKNOWLEDGEMENTS

The authors wish to offer special thanks to Irv Stumler and Tony Bellafiore of Urethane of Kentuckiana, Inc., Rick Radabanko of Sprayfoam Southwest, Dave Fritzinger of Energy Shield, Tom Tisthammer of System 7, and Steve Eddy and Leo Markwat of GVF.

REFERENCES

1. Anon. "Databank." RSI, May 1989, p. 20.

2. Boone, R. "Built-up Roofing: A Single-ply View." Contractors Roofing and Building Insulation Guide, July 1991, p. 32 - 35.

3. Carlson, J. "PVC maintenance and repair for roof system longevity." Professional Roofer, NRCA, January, 1991, p. 38 - 41.

4. Cesari, D. "Single-Ply Roofs: Eight Years Later." Proceedings of the Seventy-Sixth Annual Meeting of the Association of Physical Plant Administrators of Universities and Colleges, July 16, 1989, p. 60 - 62.

5. Dupuis, R. "Different roof systems have different failure modes." Professional Roofing, June 1990, p. 30 - 33.

6. Goldratt, E. and Cox, J. (1986). "The Goal." North River Press, Croton-on-Hudson, NY.

7. Kashiwagi, D. T. and Moor W. C. (1990) "Application of Technology in Roofing." Unpublished paper, Arizona State University, College of Engineering, Department of Industrial/Management Systems.

8. Kashiwagi, D. T., Moor, W. C., and Beaumariage, T., "The Development Of An Expert System/Database For PUF Roof System Specification, Design, and Analysis." Third International Symposium On Roofing Technology, NRCA and NBS, Montreal Canada, April 17 - 19, 1991.

9. Kashiwagi, D. T. (1983). "The Economic Feasibility of the Polyurethane Foam Roof System," MS Thesis, Arizona State University, Tempe, AZ.

10. Kashiwagi, D. T. (1991). "Development of a Performance Based Design/Procurement System For Nonstructural Facility Systems." PhD Dissertation, Arizona State University, Tempe, AZ.

11. Kolseth, C. and Nuno J. P. (1990). "Intelligent Decision Environment to Facilitate the Introduction of New Manufacturing Technology", Proceedings of the CIM 90 Conference, France.

12. Martin, J., Rossister, W., Embree, E. "Is your adhesive layer thick enough?" Professional Roofing magazine, NRCA, May 1991, p. 30 - 37.

13. Porter, M. (1985). "Competitive Advantage, Creating and Sustaining Superior Performance." (NY: Free Press).

14. Zeleny, M. (1982). "Multiple Criteria Decision Making." (New York: McGraw-Hill).