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MULTI-ATTRIBUTE CONTROL OF CONSTRUCTION ACTIVITIES

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The control of construction activities usually involves monitoring and manipulating multiple attributes at the same time. In this paper, a multi-attribute real-time control system for construction activities is presented. The proposed system monitors and controls two or more attributes, utilizing a set of single-attribute control systems operating in parallel. The proposed system includes a conflict resolution unit which is responsible for resolving any conflicting commands resulting from the individual parallel control systems. A feed-forward control loop is also integrated in the proposed model. The feed-forward loop assesses the controllability of the system, and either permit operation, stop operation or suggests adjusting the control standards.

KEYWORDS: Activity, Assessment, Conflict, Construction, Control, Fuzzy, Likelihood, Probability, Process, Safety, Uncertainty.

INTRODUCTION

A construction activity could be modelled as a structure system with several attributes of interest (Ayyub and Hassan 1991a). Each one of these attributes is modelled using a set of variables that directly affect its condition. Knowing the states of these variables, an assessment of the attribute condition could be evaluated (Ayyub and Hassan 1991b). Using a fuzzy-based control strategy, each attribute could be monitored and controlled within predetermined control standards (Ayyub and Hassan 1991c). However, some variables are very difficult to control if not impossible. For example, weather condition is considered an uncontrollable variable. Thus, a further division of the involved variables as controllable and uncontrollable is needed. The control strategy developed by Ayyub and Hassan (1991c) handles a single attribute at a time. However, in most cases the user faces situations where two or more attributes should be monitored and controlled at the same time. In this paper, a generalization of the single attribute control system is proposed. Multi-attribute control involves several single-attribute controllers performing their functions in parallel. Each controller is responsible for handling one of the attributes of interest. An additional conflict resolution unit, which is responsible for analyzing the different control actions resulting from the single-attribute controllers, was developed and integrated with the proposed control system. For two or more controllers resulting in conflicting actions applied to the same critical control variable, the proposed unit should resolve this conflict. The conflict resolution unit should result in a compromise control action that satisfies all the involved attributes as close as possible. The proposed algorithm constructs several alternatives that represent combinations of the attribute conditions resulting from the corresponding individual control actions. A performance utility function is then used in rating these alternatives. Then, a utility ranking is performed in order to select the compromise or best alternative. The selection of this alternative is based on the maximization of the corresponding utility rank. A feed-forward loop is added to the previously developed control system. The proposed control loop provides a decision concerning the operation of the controlled system. The resulting decision is based on the controllability of the construction activity.

CONTROLLABLE AND UNCONTROLLABLE VARIABLES

In this paper, variables are divided into controllable variables which have adjustable states, and uncontrollable variables which have unadjustable states. For example, the variable Labor Experience is considered a controllable variable, whereas the variable Weather Condition is considered an uncontrollable variable. Although uncontrollable variables cannot be adjusted, they should be included in the condition assessment of attributes. Their effect is considered in a similar manner as for controllable variables, as explained by Ayyub and Hassan (1991b). For some uncontrollable variables it is even difficult to directly measure their states. Such variables are referred to as unobservable variables. For example, Weather Condition is an uncontrollable unobservable variable. In order to be able to measure the state of such a variable, further decomposition should be performed. An unobservable variable should have a set of observable measures. For example, Weather Condition could be decomposed into, for example, Temperature, Rain intensity, and Wind velocity. Each one of these measures can be easily observed resulting in an image of the weather condition at a certain support instant. An observation look-up table is used for the purpose of evaluating the weather condition for a set of observations. Table 1 shows an example observation table that relates the temperature, rain intensity and wind velocity to a corresponding weather condition. For any construction activity, several uncontrollable variables could be defined. In addition to Weather Condition, Government Regulations and Material Quality may be considered as uncontrollable variables that have an impact on the attribute condition of the activity. For more than one uncontrollable unobservable variable, it would be helpful to have

Table 1 Observation Table

Temperature (°F)	*Rain Intensity*	*Wind Velocity*	*Weather Condition*
30	Moderate	Medium	Fair
30	Low	Low	Moderate
30	High	Medium	Fair
40	High	High	Very Fair
90	Very Low	Very Low	Fair

a relational diagram that visually model the relation between the different variables, for example an influence diagram.

INFLUENCE DIAGRAM MODEL

The proposed feed-forward control loop was developed as a solution to a decision problem. The control loop should result in a decision concerning the operation of the controlled activity. The decision should be either to proceed operation, stop operation or adjust control standards. This decision is based on the controllability of the activity, knowing the states of the uncontrollable variables. Influence diagrams are considered to be effective in this type of decision analysis. They represent a graphical representation of the inter-dependencies among the involved variables (Agogino 1987, Henrion 1990, Howard 1990, Matheson 1990, and Shachter 1986). An influence diagram is composed of a set of nodes interconnected by directed arcs (Howard 1990, and Matheson 1990). The nodes represent the involved random variables and decisions, and the arcs between the nodes represent the inter-dependencies among the corresponding variables. Influence diagrams can be utilized at three different levels of interpretation, namely, relational, functional and numerical (Agogino 1987). For the purpose of this study, the influence diagram is merely used for the purpose of graphically representing the flow of information within the decision problem. Thus, the influence diagram is defined at the first relational level. At this level, the diagram establishes relations among variables, their observable measures, the decision criterion and the resulting decision.

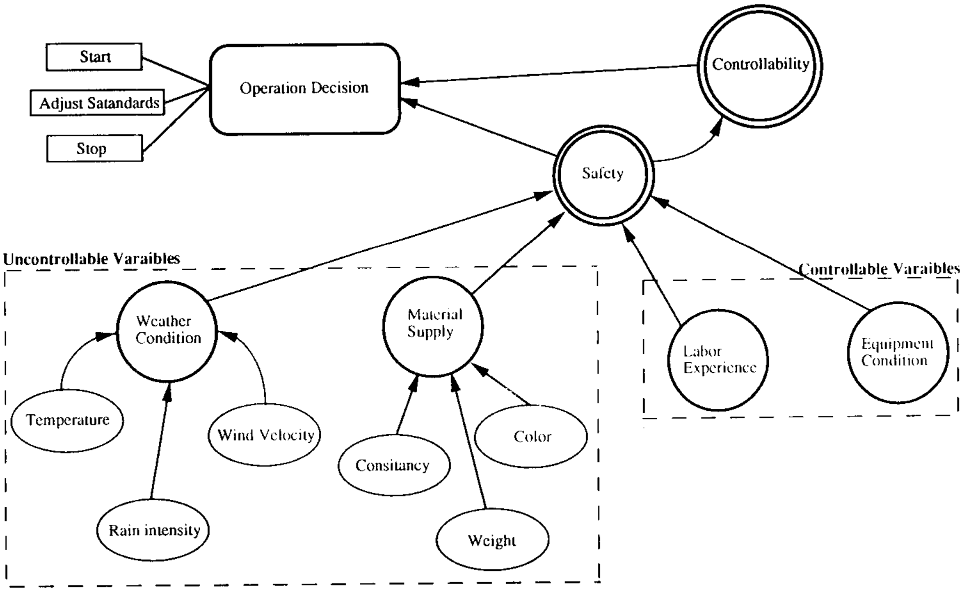
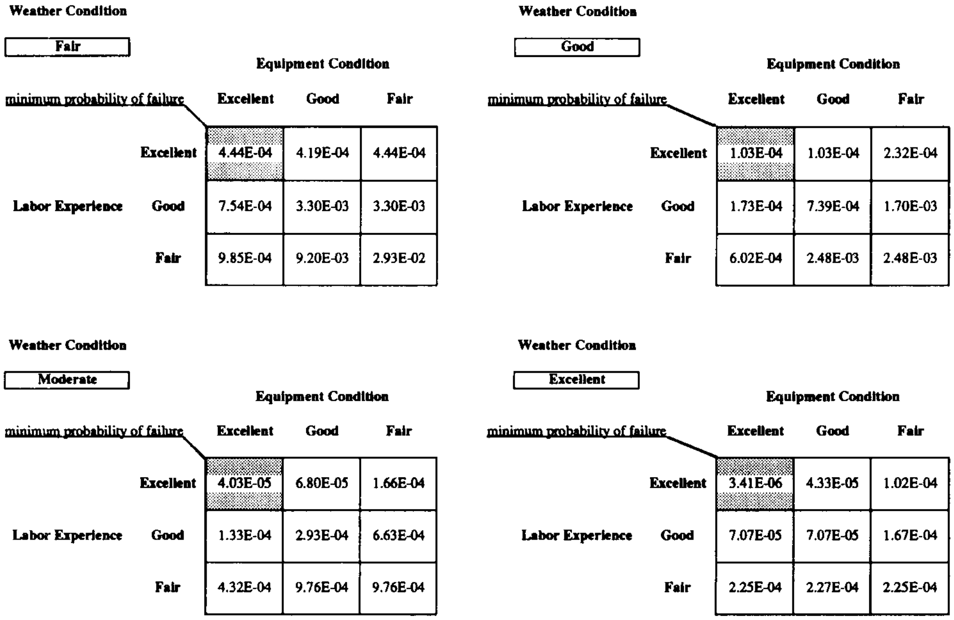


Figure 1 An example influence diagram model for safety of construction activities

Figure 1 shows an example influence diagram for the feed-forward loop and the resulting decision. In this figure, the variables are divided into the two main groups, i.e., controllable and uncontrollable. Arrows between random variables indicate interdependencies among these variables, while the lack of arrows indicate independencies of the corresponding variables. Arrows between random variables and decision nodes indicate the knowledge of the states of these variables at the time the decision is made. For uncontrollable unobservable variables, their observable measures are also shown in relation to the decision problem. The diagram represents the flow of information which leads to the required decision.

CONTROLLABILITY

The feed-forward loop represents a graphical framework of a decision problem where a decision about the operation of the activity is made. The decision criterion as outlined earlier is the controllability of the attribute of interest. Hence, a definition of the controllability of an activity is required, together with a measure which could be used for its quantification. Controllability could be defined as the ability to limit the activity's attribute condition within the required standards, using state or behavior function manipulation. Based on this definition and using the failure likelihood matrix, resulting from the safety condition assessment (Ayyub and Hassan 1991b), a controllability measure for safety, as an example, could be defined. The failure likelihood matrix, as defined by Ayyub and Hassan (1991b), represents the probability of failure, i.e., the safety measure, for each possible combination of states of the involved variables. For example, for two controllable variables, namely, Labor Experience



Weather Condition

Fair

minimum probability of failure		**Equipment Condition** **Excellent**	**Good**	**Fair**
	Excellent	▨ 4.44E-04	4.19E-04	4.44E-04
Labor Experience	**Good**	7.54E-04	3.30E-03	3.30E-03
	Fair	9.85E-04	9.20E-03	2.93E-02

Weather Condition

Good

minimum probability of failure		**Equipment Condition** **Excellent**	**Good**	**Fair**
	Excellent	▨ 1.03E-04	1.03E-04	2.32E-04
Labor Experience	**Good**	1.73E-04	7.39E-04	1.70E-03
	Fair	6.02E-04	2.48E-03	2.48E-03

Weather Condition

Moderate

minimum probability of failure		**Equipment Condition** **Excellent**	**Good**	**Fair**
	Excellent	▨ 4.03E-05	6.80E-05	1.66E-04
Labor Experience	**Good**	1.33E-04	2.93E-04	6.63E-04
	Fair	4.32E-04	9.76E-04	9.76E-04

Weather Condition

Excellent

minimum probability of failure		**Equipment Condition** **Excellent**	**Good**	**Fair**
	Excellent	▨ 3.41E-06	4.33E-05	1.02E-04
Labor Experience	**Good**	7.07E-05	7.07E-05	1.67E-04
	Fair	2.25E-04	2.27E-04	2.25E-04

Figure 2 Failure likelihood matrix

and Equipment Condition and one uncontrollable variable, namely, Weather Condition, Figure 2 shows the corresponding failure likelihood matrix. For such a case, the minimum probability of failure for the current state of uncontrollable variable, is used as the controllability measure. Figure 2 shows those probabilities of failure in shaded areas. Therefore, this probability of failure represents the best safety measure that could be attained under the current state of uncontrollable variable, i.e., Weather Condition. This safety measure can be attained by adjusting the states of the controllable variables to their ultimate values. For the example under consideration, the probability of failure for the combination of Excellent and Excellent for the current state of Weather Condition is the controllability measure. If this probability of failure is less than the required control standard, the activity is considered to be controllable and the feed-forward loop permits the activity to proceed. However, if the probability of failure is greater than the required control standard, the activity is considered to be uncontrollable and the decision should be either to adjust the control standards or stop the activity. If the final decision turned out to be to stop operation, this should last until the next sampling cycle which should be activated whenever a change in the state of the uncontrollable variable is detected.

CONTROL-STANDARD ADJUSTMENT

In the case of an uncontrollable activity, the control loop provides the user with one of two options. The first option is terminating operation and the second option is adjusting the control standards. This option is interactively decided by the user depending on the effect of the current state of the uncontrollable variable on the operation of the activity. It also depends on any allowed levels of violation in satisfying the required control standards. The standard adjustment is performed in power order steps. The amount of adjustment required to render a controllable activity is subjectively determined based on how far the minimum attribute condition is relative to the current standard and the value of the current standard. This adjustment factor is tabulated in the control adjustment matrix as shown in Table 2. This matrix should be subjectively evaluated by a knowledgeable expert. Once the adjustment option is selected by the user, the system automatically look-up the corresponding adjustment factor from the control adjustment matrix and apply it to the current control standard. Hence, resulting in a controllable activity which is then permitted to proceed by the control loop. The overall structure and logic of the discussed feed-forward control loop

Table 2 Failure likelihood matrix

Failure Likelihood Level		*Current Control Standard*					
		1.00E-06	*1.00E-05*	*1.00E-04*	*1.00E-03*	*1.00E-02*	*1.00E-01*
Error Level	0	0	0	0	0	0	0
	1	2	1	0	0	0	0
	2	3	2	1	0	0	0
	3	3	2	1	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
	7	0	0	0	0	0	0

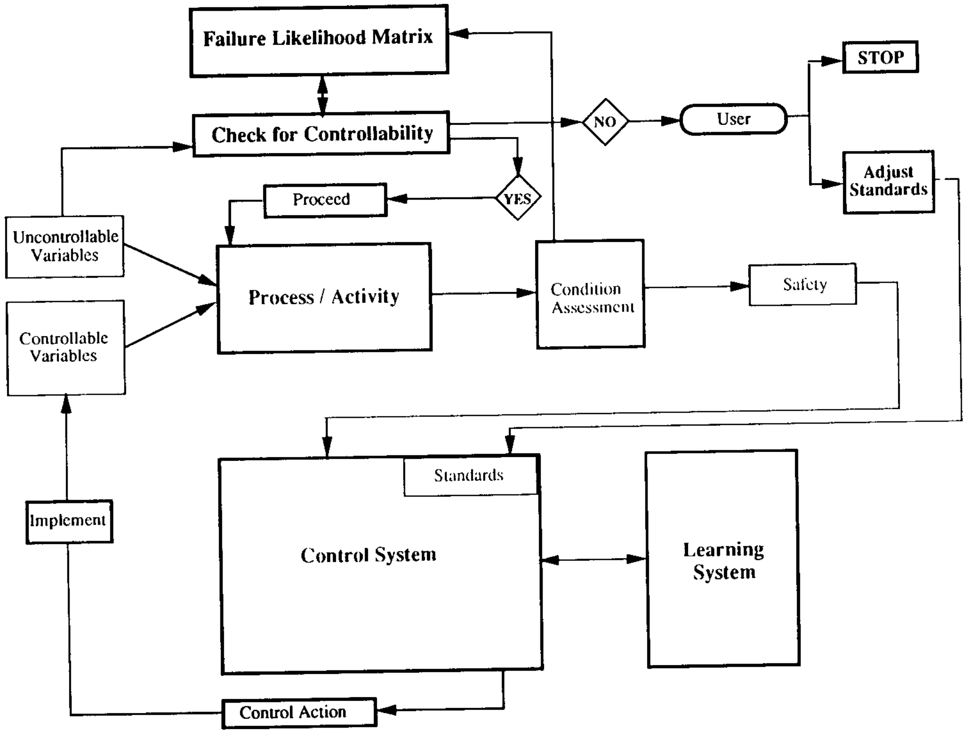


Figure 3 Block diagram for feed-forward loop

is shown in a block diagram in Figure 3. In this diagram, the feed-forward loop together with the feedback control loop are schematically shown with their mutual effects on the controlled activity.

MULTI-ATTRIBUTE CONTROL STRATEGY

Ayyub and Hassan (1991c) developed a fuzzy-based real-time control system for construction activities. This system was developed to monitor and control a single attribute of interest as shown in Figure 3. However, in most construction projects, it is essential to monitor and control two or more attributes at the same time. Figure 4 shows a block diagram of the structure of the proposed multi-attribute control system. The generalized system comprises several parallel single-attribute control systems. Each system is responsible for monitoring and controlling a single attribute, and comprises a suitable rule-base that is related to the attribute of interest and the corresponding control standard. Figure 4 shows a two-attribute control system where safety and quality are the attributes of interest. Both rule-bases share a common inference engine which is responsible for evaluating the control action, knowing the error and change in error with respect to a predetermined control standard (Ayyub and Hassan 1991c). In general, each attribute should utilize a separate rule-base. However, in

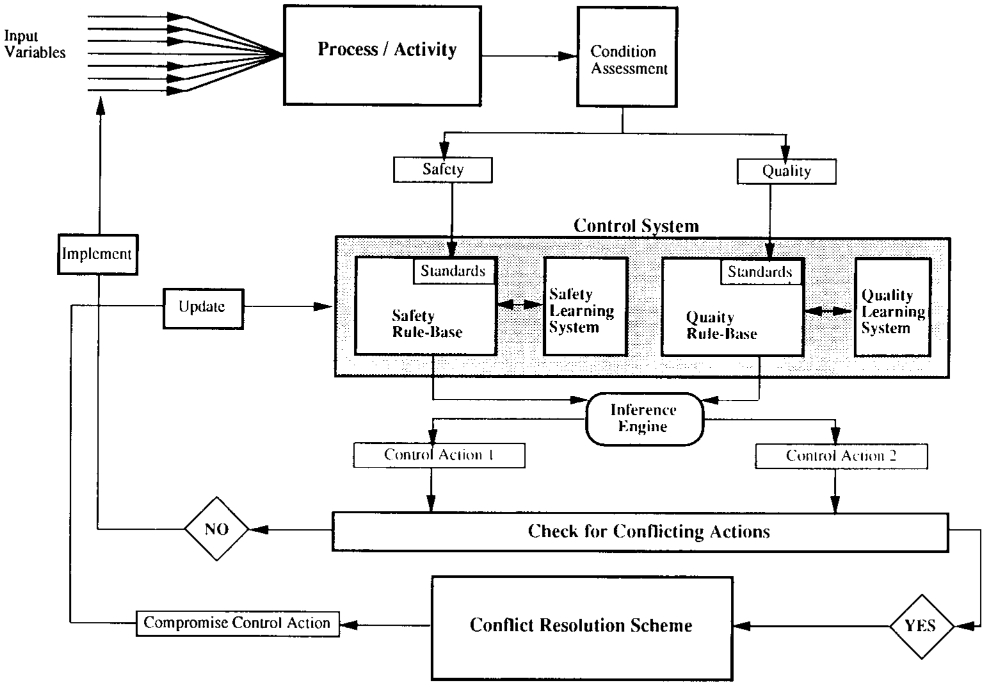


Figure 4 Multi-attribute control strategy

some special cases certain attributes may end up sharing the same rule base. A self-learning system should be established for each control system. Different learning systems utilize relevant performance matrices depending on the control attribute under consideration (Ayyub and Hassan 1991c). Self-learning systems are responsible for expanding and updating the individual rule-bases. The multi-attribute control system shown in Figure 4 results in multiple control actions. Each control system suggests a generally unique control action applicable to its critical control variable. The critical control variables are selected based on their relative impact and importance with respect to the controlled attributes (Ayyub and Hassan 1991c). Some situations may arise where the same variable could be selected by two or more control systems as the critical control variable. In this case, if the different control actions are not identical, which is the general case, a conflict arises. Thus, it is essential to include a conflict resolution unit which can resolve such conflicting commands from the parallel controllers. The proposed unit should be able to develop a compromise alternative that satisfies all the involved attributes as close as possible. The remaining part of this paper is devoted to the development and discussion of the conflict resolution algorithm.

CONFLICT RESOLUTION

Because of multiple control actions, conflicts may arise if the same variable is selected as a critical control variable for two or more attributes. In order to resolve any conflicting actions, a conflict resolution algorithm is needed. Several algorithms were studied in the reviewed literature, with their own advantages and disadvantages (Cheng and McInnis 1980, Efstathiou and Rajkovic 1979, and Zimmermann 1987). However, it is generally agreed upon that multi-attribute decision problems usually require a problem dependent algorithm. Most of the reviewed algorithms were related to crisply defined decision problems. However, for the application under consideration an algorithm that is capable of handling uncertain decision problems is required. The conflict resolution algorithm utilized in this study is based on the work of Efstathiou and Rajkovic (1979). The proposed algorithm develops a compromise control action which satisfies all involved attributes as close as possible. This compromise solution is one of several alternatives developed by the algorithm. Each alternative is then rated using a fuzzy utility function. A rating procedure is then utilized in order to rank the individual alternative utilities for the purpose of selecting the solution that maximizes the utility rating.

Individual Alternative Definition

In multi-attribute control, a control action results from each individual single-attribute control system. In general, these actions are different and may or may not be applied to the same critical control variable. If these control actions were applied to the same variable, the conflict resolution scheme should be activated. Each control action, when applied to the critical control variable results in a new state for that variable. This new state, together with the states of the other involved variables, renders a new condition for each controlled attribute (Ayyub and Hassan 1991b). For example, a two-attribute control system is shown in Figure 4, where safety and quality are considered the attributes of interest. As shown in the figure, assuming that the same critical control variable was determined for both attributes, each control system results in a different control action which are identified as control action 1 and control action 2. These actions are suggested by the control systems in order to improve their respective attribute condition. Each control action results in a new state of the critical control variable, which together with the states of the other variables, utilizing a condition assessment methodology, results in a new condition for the safety and the quality attributes (Ayyub and Hassan 1991b). In other words, the attribute has different potential conditions resulting from the suggested control actions. Hence, two alternatives result, each represents a combination of safety and quality conditions that corresponds to a certain control action. The resulting condition assessments are evaluated in a fuzzy set format (Ayyub and Hassan 1991b). Thus, the i^{th} alternative is defined as the Cartesian product of the individual attribute condition fuzzy sets. This could be defined mathematically as

$$\mu_{Ai}(x,y) = \text{MIN}\,[\mu_{T1}(x), \mu_{T2}(y)] \tag{1}$$

where $\mu_{Ai}(x,y)$ = membership value of the combination of element x in the first attribute condition fuzzy set and element y in the second attribute condition fuzzy set of the i^{th}

Control Action	Safety	Quality
1	3.98E-06	Good
2	1.54E-06	Excellent

Alternative 1			Good Quality										
			0	1	2	3	4	5	6	7	8	9	10
			0	0.3	0.5	1	0.8	0	0	0	0	0	0
Safety = 3.98E-06	1.00E-06	0.8	0.00	0.30	0.50	0.80	0.80	0.00	0.00	0.00	0.00	0.00	0.00
	1.00E-05	0.64	0.00	0.30	0.50	0.64	0.64	0.00	0.00	0.00	0.00	0.00	0.00
	1.00E-04	0.16	0.00	0.16	0.16	0.16	0.16	0.00	0.00	0.00	0.00	0.00	0.00
	1.00E-03	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.00E-02	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.00E-01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Alternative 2			Excellent Quality										
			0	1	2	3	4	5	6	7	8	9	10
			0	0	0	0	0	0	0	0	0.8	0.9	1
Safety = 1.54E-06	1.00E-06	0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50
	1.00E-05	0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50
	1.00E-04	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.64	0.64
	1.00E-03	0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.80	0.80
	1.00E-02	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.64	0.64
	1.00E-01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 5 Individual alternative definition

alternative; MIN = minimum operator; μ_{T1} (x) = membership value of element x in the first attribute condition fuzzy set; and μ_{T2} (y) = membership value of element y in the second attribute condition fuzzy set. For example, Figure 5 shows safety and quality assessments, as example control attributes, resulting from two conflicting control actions. Each one of these assessments is a single point estimate of a fuzzy attribute condition, resulting by a deffuzzyfication procedure (Ayyub and Hassan 1991b). In order to preserve the underlying uncertainties involved in the condition assessment methodology, the fuzzy attribute condition is utilized instead of its single point estimate. Each combination of safety and quality represents a unique alternative which is defined using the Cartesian product as defined in equation 1. A fuzzy utility function is then used in rating the individual alternatives.

Rating of Alternatives

Knowing the individual alternatives resulting from the conflicting control actions, a rating system should be developed by which each alternative could be evaluated. Because of the use of linguistic measures and quantifiers in construction activities, a fuzzy-based utility function is a suitable approach for handling the rating problem. A fuzzy utility function subjectively assigns utility levels with certain degrees of belief for all potential fuzzy alternatives (Efstathiou and Rajkovic 1979). It is then an essential step to develop the universe of the fuzzy utility function. In this study, the universe of the fuzzy utility function is defined as

$$U = \{\text{Very High, High, Medium-High, Medium, Medium-Low, Low, Very Low}\} \quad (2)$$

where U = universe of the fuzzy utility function; and Very High, High, .., Very Low = linguistic measures defined using fuzzy set theory as follows:

$$\text{Very High} = \{8|0.64, 9|0.81, 10|1.0\} \quad (3\text{-a})$$
$$\text{High} = \{8|0.8, 9|0.9, 10|1.0\} \quad (3\text{-b})$$
$$\text{Medium-High} = \{5|0.3, 6|0.5, 7|1.0, 8|0.5, 9|0.3\} \quad (3\text{-c})$$
$$\text{Medium} = \{3|0.5, 4|0.8, 5|1.0, 6|0.8, 7|0.5\} \quad (3\text{-d})$$
$$\text{Medium-Low} = \{1|0.3, 2|0.5, 3|1.0, 4|0.5, 5|0.3\} \quad (3\text{-e})$$
$$\text{Low} = \{0|1.0, 1|0.9, 2|0.8\} \quad (3\text{-f})$$
$$\text{Very Low} = \{0|1.0, 1|0.64, 2|0.81\} \quad (3\text{-g})$$

where Very High, High, .., Very Low = linguistic measures on a scale from 1 to 10, in which 0 = the lowest level and 10 = the highest level; and 0.1, 0.2, .., 1.0 = degrees of belief that the corresponding elements belong to the measures. Expert judgement is then used in the development of the fuzzy utility function where a performance utility matrix results. Table 3 shows an example performance utility matrix. The matrix handles the two attributes of interest, safety and quality. Each potential combination of attribute conditions is assigned a degree of belief that results in a certain utility level. In this context, this utility function is modelled as a fuzzy relation between the universe of the Cartesian product of the attributes of interest and the universe of the utility function. In this example, this fuzzy relation results in a three-dimensional matrix. Knowing the fuzzy utility function and the individual alternatives, the composition of fuzzy relations, developed by Zadeh (1965 and 1973), could be utilized in order to evaluate a fuzzy utility measure for each potential alternative. Thus, the fuzzy utility measure for a certain alternative is defined as

$$\mu_{U_j}(U_i) = \underset{\text{for all}(x,\, y)}{\text{MAX}} \ \text{MIN}\left(\mu_{A_j}(x, y), \mu_{3R}(x, y, u_i)\right)$$

where $\mu_{Uj}(u_i)$ = membership value of the utility level u_i in the fuzzy utility measure of the j^{th} alternative; MAX = maximum operator; MIN = minimum operator; $\mu_{Aj}(x,y)$ = membership value of element (x,y) in the j^{th} alternative defined in equation 1; and $\mu_{3R}(x,y,u_i)$ = membership value of element (x,y) with a utility level u_i, defined by a three-dimensional fuzzy relation in the performance utility matrix. For the example under consideration, the resulting fuzzy utility measure for the first alternative is given as

$$\begin{aligned}\mu_{U1}(.) = \{&\text{Very High}|0.0, \text{High}|0.0, \text{Medium-High}|0.0, \text{Medium}|0.64,\\ &\text{Medium-Low}|0.64, \text{Low}|0.8, \text{Very Low}|0.0\}\end{aligned} \quad (5)$$

Because the elements of the universe of the fuzzy utility function are linguistic measures, defined by fuzzy sets themselves, an adjustment process is required in order to evaluate a fuzzy utility measure with numerical elements. The rational behind such adjustment is based on the fact that further processing and ranking of the individual utility measures is required. However, if the elements remain in a linguistic format, such processing would be difficult.

Table 3 Performance utility matrix (Fuzzy utility function)

		Quality Fuzzy Condition										
Very High Utility Level		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
	1E-06	0	0	0	0	0	0	0	0	1	1	1
	1E-05	0	0	0	0	0	0	0	0	1	1	1
	1E-04	0	0	0	0	0	0	0	0	0	0	0
Safety Fuzzy Condition	1E-03	0	0	0	0	0	0	0	0	0	0	0
	1E-02	0	0	0	0	0	0	0	0	0	0	0
	1E-01	0	0	0	0	0	0	0	0	0	0	0
High Utility Level												
	1E-06	0	0	0	0	0	0	0	1	0	0	0
	1E-05	0	0	0	0	0	0	0	1	0	0	0
	1E-04	0	0	0	0	0	0	0	1	1	1	1
Safety Fuzzy Condition	1E-03	0	0	0	0	0	0	0	0	0	0	0
	1E-02	0	0	0	0	0	0	0	0	0	0	0
	1E-01	0	0	0	0	0	0	0	0	0	0	0
Medium-High Utility Level												
	1E-06	0	0	0	0	0	1	1	0	0	0	0
	1E-05	0	0	0	0	0	0	1	0	0	0	0
	1E-04	0	0	0	0	0	0	1	0	0	0	0
Safety Fuzzy Condition	1E-03	0	0	0	0	0	0	1	1	1	1	1
	1E-02	0	0	0	0	0	0	0	0	0	0	0
	1E-01	0	0	0	0	0	0	0	0	0	0	0
Medium Utility Level												
	1E-06	0	0	0	0	0	0	0	0	0	0	0
	1E-05	0	0	0	0	1	1	0	0	0	0	0
	1E-04	0	0	0	0	0	1	0	0	0	0	0
Safety Fuzzy Condition	1E-03	0	0	0	0	0	1	0	0	0	0	0
	1E-02	0	0	0	0	0	1	1	0	0	0	0
	1E-01	0	0	0	0	0	0	0	0	0	0	0
Medium-Low Utility Level												
	1E-06	0	0	0	0	0	0	0	0	0	0	0
	1E-05	1	1	1	1	0	0	0	0	0	0	0
	1E-04	1	1	1	1	1	0	0	0	0	0	0
Safety Fuzzy Condition	1E-03	0	0	0	0	1	0	0	0	0	0	0
	1E-02	0	0	0	0	1	0	0	1	1	1	1
	1E-01	0	0	0	0	1	1	0	0	0	0	0
Low Utility Level												
	1E-06	1	1	1	1	1	0	0	0	0	0	0
	1E-05	0	0	0	0	0	0	0	0	0	0	0
	1E-04	0	0	0	0	0	0	0	0	0	0	0
Safety Fuzzy Condition	1E-03	1	1	1	1	0	0	0	0	0	0	0
	1E-02	0	0	0	1	0	0	0	0	0	0	0
	1E-01	0	0	0	1	0	0	1	1	1	1	1
Very Low Utility Level												
	1E-06	0	0	0	0	0	0	0	0	0	0	0
	1E-05	0	0	0	0	0	0	0	0	0	0	0
	1E-04	0	0	0	0	0	0	0	0	0	0	0
Safety Fuzzy Condition	1E-03	0	0	0	0	0	0	0	0	0	0	0
	1E-02	1	1	1	0	0	0	0	0	0	0	0
	1E-01	1	1	1	0	0	0	0	0	0	0	0

In addition, in order to be able to graphically represent the different utility measures, these measures should be expressed using numerical elements instead of linguistic measures. Therefore, using the fuzzy set definition of the individual linguistic utility elements, i.e., Very High, High, .., Very Low, and the degree of belief of each element evaluated in equation 3, the following adjusted fuzzy set for each individual element results

$$\mu^{a}_{uij}(.) = \text{MIN}\,(\mu_{Uj}(u_i),\mu_{ui}(.)) \tag{6}$$

where $\mu^{a}_{uij}(.)$ = adjusted membership function of the ith linguistic utility element u_i in the fuzzy utility measure of the jth alternative; MIN = minimum operator, $\mu_{Uj}(u_i)$ = membership value of the ith linguistic utility element u_i in the fuzzy utility measure of the jth alternative defined by equation 4; and $\mu_{ui}(.)$ = membership function of the ith linguistic utility element u_i, i.e., Very High, High, .., Very Low. For example, for the Medium linguistic utility measure given by $\mu_{Medium}(.) = \{3|0.5, 4|0.8, 5|1.0, 6|0.8, 7|0.5\}$, and having the degree of belief of 0.64 in the fuzzy utility measure of the first alternatrive, according to equation 5, the adjusted fuzzy set definition resulting from equation 5 is given as

$$\mu^{a}_{Medium}(.) = \{3|0.5, 4|0.64, 5|0.64, 6|0.64, 7|0.5\} \tag{7}$$

A problem then arises where each numerical element in the fuzzy utility measure might have more than one degree of belief. Thus, an aggregation procedure is required in order to evaluate an overall fuzzy utility measure for each individual alternative. Utilizing the maximum operator as an aggregation tool, the aggregated fuzzy utility measure is defined as

$$\mu^{g}_{U_j}(x) = \underset{\text{for all } u_i}{\text{MAX}}\ \mu^{a}_{u_{ij}}(x) \tag{8}$$

where $\mu^{g}U_j$ = membership value of element x in the overall fuzzy utility measure of the jth alternative; MAX = maximum operator; and $\mu^{g}_{uj}(x)$ = adjusted membership value of element x in the linguistic utility element u_i in the fuzzy utility measure of the jth alternative. For the first alternative in the example under consideration, Table 4 shows the adjusted linguistic measure fuzzy sets and their corresponding degrees of belief in the fuzzy utility measure. Applying the aggregation procedure as defined in equation 8, the following overall fuzzy utility measure results:

$$\mu^{g}U_1(.)\ \{ 0|0.8, 1|0.8, 2|0.8, 3|0.64, 4|0.64, 5|0.64, 6|0.64, 7|0.5, 8|0.0, 9|0.0, 10|0.0\} \tag{9}$$

Figure 6 shows a block diagram of the structure and logic of the conflict resolution procedure. the figure shows the individual alternatives and their resulting utility measures. The final step in the conflict resolution procedure should deal with ranking the individual utility measures in order to select the best alternative.

Table 4 Adjustment of linguistic elements of fuzzy utility measures

Adjustment of Linguistic Elements of Fuzzy Utility Measures		*Adjusted Linguistic elements fuzzy sets*						
		Very High	*High*	*Medium-High*	*Medium*	*Medium-Low*	*Low*	*Very Low*
Degrees of Belief of Linguistic Elements in Fuzzy Utility Measure 1		*0.00*	*0.00*	*0.00*	*0.64*	*0.64*	*0.80*	*0.00*
Numerical Elements in Fuzzy Utility Measure 1	0	0.00	0.00	0.00	0.00	0.00	0.80	0.00
	1	0.00	0.00	0.00	0.00	0.30	0.80	0.00
	2	0.00	0.00	0.00	0.00	0.50	0.80	0.00
	3	0.00	0.00	0.00	0.50	0.64	0.00	0.00
	4	0.00	0.00	0.00	0.64	0.50	0.00	0.00
	5	0.00	0.00	0.00	0.64	0.30	0.00	0.00
	6	0.00	0.00	0.00	0.64	0.00	0.00	0.00
	7	0.00	0.00	0.00	0.50	0.00	0.00	0.00
	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	10	0.00	0.00	0.00	0.00	0.00	0.00	0.00

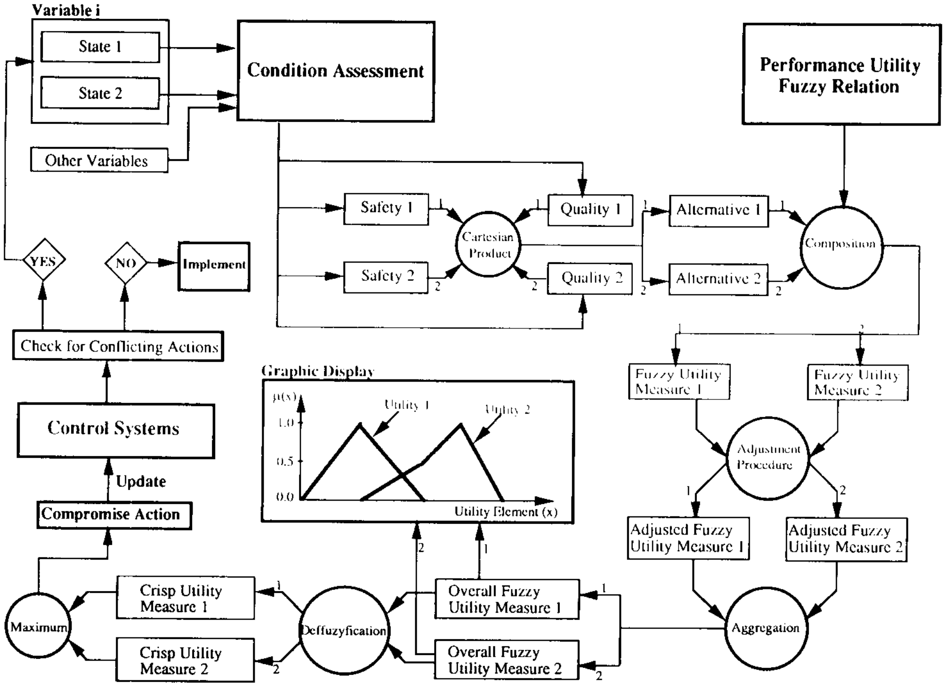


Figure 6 Block diagram of conflict resolution scheme

Utility Ranking

Knowing the overall fuzzy utility measure for each individual alternative, a ranking procedure is then utilized in order to select the best compromise solution. In this study, a defuzzyfication process is utilized as a ranking procedure. Since utility measures have been already evaluated in a fuzzy set format in order to preserve the underlying uncertainties, single point estimates could be evaluated, at this stage, without loosing any available information. The resulting single point estimate is used as a rank that represents the utility of the corresponding alternative. This rank is then used as a basis for selecting the best compromise alternative. A defuzzyfication procedure developed by Ayyub and Hassan (1991b) is utilized in this study in order to evaluate the corresponding single point estimate. The defuzzyfication procedure is defined as

$$R_j = \sum_{\text{all } x} \frac{\mu^g_{Uj}(x)\, x}{\mu^g_{Uj}(x)} \tag{10}$$

where R_j = single point estimate, i.e., rank, of the overall fuzzy utility measure of the jth alternative; and $\mu^g U_j(x)$ = membership value of element x in the overall fuzzy utility measure of the jth alternative. Figure 6 shows this procedure together with a graphic display interface which also provides the user with the graphical representation of the individual fuzzy utility measures. Figure 7 shows an example graphical output for the fuzzy utility measures of the

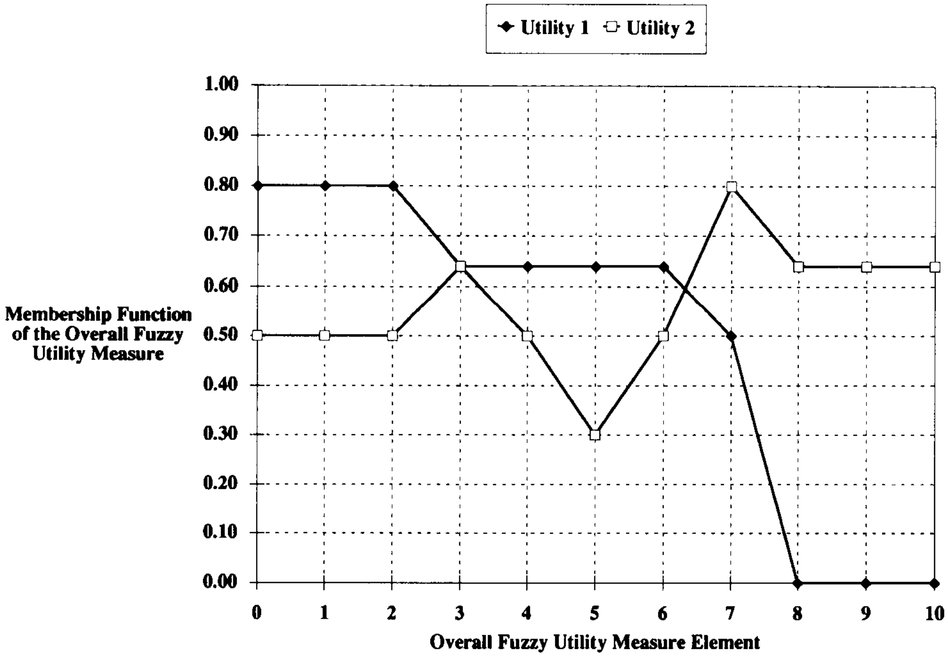


Figure 7 Graphical display of fuzzy utility measures

two potential alternatives discussed in Table 4. The graphical display provides yet another dimension for selecting the best compromise alternative. In general, the best compromise alternative is the one resulting in the maximum utility measure. Thus, a maximization operator is utilized in selecting the final compromise alternative. The rank of the compromise utility is then defined as

$$R_c = \underset{\text{for all } j}{\text{MAX}} \; R_j \tag{11}$$

where R_c = rank of the compromise utility; MAX = maximum operator applied for all j which varies from 1 to the number of potential alternatives; and R_j = rank of the overall fuzzy utility measure of the j^{th} alternative defined in equation 10. Based on the selected alternative, all single-attribute control systems should be updated. For each control system, if the compromise alternative renders an attribute condition that does not satisfy the control standards, then a new critical control variable should be selected and adjusted. The conflict resolution scheme should then be re-activated if further conflicting actions were detected. However, if no conflicts resulted from the control systems updating, the compromise alternative should be implemented and the control cycle is considered complete. Figure 6 shows the updating procedure required for the different control systems.

SUMMARY AND CONCLUSIONS

In this paper, a multi-attribute control system for construction activities is presented. The proposed control system is a generalization of a single-attribute fuzzy-based real-time control system developed by Ayyub and Hassan (1991c). The proposed system monitors and controls two or more attributes, utilizing a set of single-attribute control systems operating in parallel. The multi-attributer control system includes an additional conflict resolution unit which is responsible for resolving any conflicting commands resulting from the individual parallel control systems. The conflict resolution unit develops a compromise control action which satisfies all involved attributes as close as possible. The compromise solution is one of several alternatives developed by the algorithm. Each alternative represent a combination of potential attribute conditions that corresponds to a certain control action. Each alternative is then rated using a fuzzy utility function. A defuzzyfication procedure is then utilized in order to rank the individual utility measures. The alternative resulting in the maximum utility rank is then selected as the compromise solution. The individual single-attribute control systems are then updated in order to ensure that they are meeting their control standards. A feed-forward control loop is proposed. The feed-forward loop is designed as an integral component of a previously developed feedback fuzzy-based control system. The feed- forward loop mainly assesses the controllability of the activity of interest and determines whether it should or should not proceed operation based on this information. If the feed-forward loop determines that the operation should be stopped, it provides the user with an alternate option by which an adjusted control standard could be evaluated.

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APPENDIX I. NOTATIONS

The following notations are used in this paper:

$\mu A_i(.)$ = membership function of the i^{th} alternative;
$\mu T_i(.)$ = membership function of the i^{th} fuzzy attribute condition;
$\mu^{a}_{uij}(.)$ = adjusted membership function of the i^{th} linguistic element in the fuzzy utility measure of the j^{th} alternative;
$\mu_{ui}(.)$ = membership function of the i^{th} linguistic element in the fuzzy utility measure;
$\mu_{Uj}(.)$ = membership function of the fuzzy utility measure of the j^{th} alternative;
$\mu^{g}_{Uj}(.)$ = membership function of the overall fuzzy utility measure of the j^{th} alternative;
R_c = rank of the compromise alternative;
R_j = rank of the j^{th} alternative;
u_i = i^{th} linguistic element in the fuzzy utility measure;
U = universe of the fuzzy utility function;
x = element in a fuzzy set;
y = element in a fuzzy set;