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USING THE DESIGN STRUCTURE MATRIX (DSM) AND ARCHITECTURE OPTIONS TO OPTIMIZE SYSTEM ADAPTABILITY

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1 INTRODUCTION

Systems provide value through their ability to fulfill stakeholders' needs and wants. These needs evolve over time and may diverge from a fielded system's capabilities. Thus, a system's value to its stakeholders diminishes over time. As a result, systems have to be periodically upgraded at substantial cost and disruption. *Architecture Options* (AOs) provide a quantitative means of exploring the optimal degree of design flexibility in a system to maximize its lifetime value for varied stakeholders.

2 ARCHITECTURE OPTIONS

In finance, an option is a contract whereby the contract buyer has a right (but not an obligation) to exercise a feature of the contract (the option) at future date (the exercise date), and the seller (or "writer") has the obligation to honor the specified feature of the contract. Since the option gives the buyer a right and the seller an obligation, the buyer has received something of value. The amount the buyer pays the seller for the option is called the option premium.

We start with a minimal building block, the *component*. A component is a software or hardware object with clearly defined interfaces. It encapsulates specific functionality and interacts with other components and/or with the environment. One or more components constitute a *module*. One aspect of AOs involves system modularity. Here, we consider all the modules constituting a system as options in an economic sense and seek to identify an optimal system architecture in terms of "adaptability attributes" that support recurring, originally unforeseen, upgrades of the system. We define three helpful metrics after which we demonstrate their use with an example.

Component Adaptability Factor (CAF)

As an initial approach to the issue of system adaptability, we define a metric called the *component adaptability factor* (*CAF*). We adopted standard ISO/IEC 9126-1, "Software Engineering - Product quality - Part 1: Quality model," which describes six categories of software quality. While we are concerned with a broader set of system types than pure software systems, these metrics also pertain to systems more generally. We provide a means of assimilating these metrics into a single index, where $CAF \in [0,1]$.

Component Option Value (COV)

To determine the expected option value of a module, we adapt an analogous approach used in financial options, the Black-Scholes Option Price Model [1]:

$$COV = SN\left[\frac{\ln\left(\frac{S}{X}\right)+T\left(r+\frac{\sigma^2}{2}\right)}{\sigma\sqrt{T}}\right] - Xe^{-rT}N\left[\frac{\ln\left(\frac{S}{X}\right)+T\left(r+\frac{\sigma^2}{2}\right)}{\sigma\sqrt{T}} - \sigma\sqrt{T}\right] \qquad (1)$$

where S is the component's current value, X is its expected future value, N is the standard normal distribution, σ is the standard deviation of the distribution of potential future values, T is the time horizon, and r is the risk-free interest rate. This approach has proven to be beneficial in financial contexts and seems to be a reasonable starting point for the engineering design context as well.

Interface Cost Factors (ICF)

A component's interfaces may represent one or more different types of interactions, including the transmission of physical material, mechanical force, energy, and/or information [4]. We build on this idea to determine cost factors for both internal and external interfaces ($Ii_{n,k}$ and $Ie_{n,l}$) and further suggest specifying the importance and desirability of each interaction with respect to its functional role—i.e., the intensity of the interaction on a zero to one scale. We consider the overall interface cost factor as the sum of the four individual interaction values.

3 ADAPTABILITY VALUE (AV) OF A SYSTEM ARCHITECTURE

In general, a large module composed of ten components has a lower expected option value than five smaller modules, each composed of two components. This claim is based on a special case of Merton's theorem [3], which states that for general probability distributions, the aggregate value of a "portfolio of options" is more valuable than an "option on a portfolio." Therefore, we assume that the expected economic value of the j^{th} engineering module, MAV_j, is normally distributed and related:

- Positively: to an appropriate function (for example, the vector sum) of each of n components' COVs, COV_n, each multiplied by its corresponding adaptability factor, CAF_n.
- Negatively: to an appropriate function (for example, the algebraic sum) of the expected costs associated with all (1) internal (module-to-module) interfaces, $Ii_{n,k}$, and (2) all external (module-to-environment) interfaces, $Ie_{n,l}$.

Thus, the module adaptability value of the first architecture variant is:

$$MAV_j^{(1)} = \sqrt{\sum_{n=1,2,...}(CAF_n * COV_n)^2} - \sum_{n=1,2,..}\left(\sum_{k=1,2,..} Ii_{n,k} + \sum_{l=1,2,..} Ie_{n,l}\right) \quad (2)$$

The system adaptability value of the entire first architecture variant, $AV^{(1)}$, is the sum of its modules' values:

$$AV^{(1)} = \sum_{j=1,2,...} MAV_j^{(1)} \quad (3)$$

During the optimization process we add, replace, or repackage modules in search of the highest-value architecture variant, which we designate AV^*.

The following example demonstrates an evaluation of a single architecture variant. Of course, different design solutions that combine components into different modules will yield varied system AVs.

The DSM in Figure 1 depicts a system of 10 components (A through J) with both internal and external interfaces. An output from a component is indicated by an "X" in its row, and an input to a component is indicated by an "X" in its column (e.g., component F generates an output to component B, which is seen by the latter as an input).

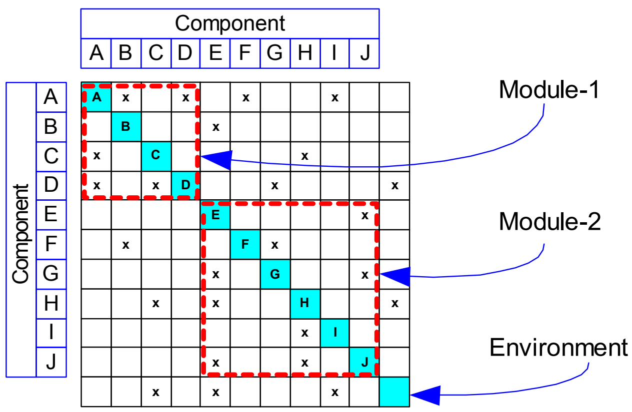

Figure 1: A system architecture variant

Figure 2 shows the DSM with the *COV* and *CAF* for each component and the interface costs ($Ii_{n,k}$ and $Ie_{n,l}$).
We use equations (2) and (3) to calculate the adaptability value of the first architecture variant. Note that interfaces within a module (e.g., from component I to component H) are hidden within the module and, therefore, do not affect cost calculations.

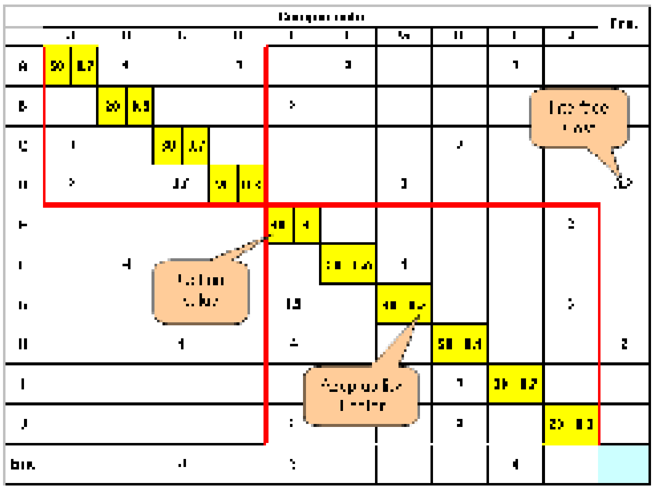

Figure 2: DSM showing COVs, CAFs, and Interface Costs

$$X_1^{(1)} = \sqrt{(50\times.7)^2 + (20\times.9)^2 + (30\times.7)^2 + (20\times.6)^2} - (3+1+2+2+3+1+4+3.2+3) = 24.0$$
$$X_2^{(1)} = \sqrt{(10\times1)^2 + (30\times.5)^2 + (40\times.2)^2 + (50\times.1)^2 + (30\times.7)^2 + (20\times.3)^2} - (2+3+3+2+1+1+4+2+4+3) = 4.8$$
$$V^{(1)} = X_1^{(1)} + X_2^{(1)} = 28.8$$

An algorithm such as a genetic algorithm would be used to generate alternative architectures (i.e., different clusterings of the components into modules). The resulting optimum architecture would likely be quite different than the optimal architecture determined via conventional techniques that only considered interfaces but not CAVs and CAFs. Future work can explore these ideas.

4 CONCLUSION

This method, which uses a DSM to document component interactions, should help designers make decisions about architecture and modularity in light of component dynamics as well as interfaces. Decisions that account for dynamics and adaptability should lead to superior long-term performance, especially in volatile environments. Many additional details of the approach will be mentioned in the presentation and are available in [2]. We have not fully validated the integrated approach on a case study, although various aspects of it have been validated in many cases.

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Using the DSM and Architecture Options to Optimize System Adaptability

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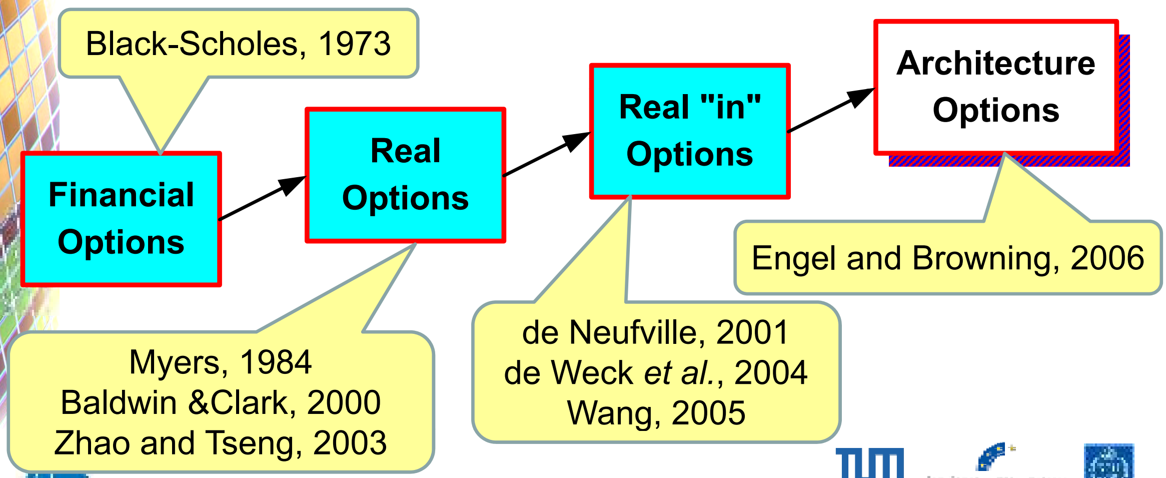
Research Context: Design for Adaptability

- Systems provide value through their ability to fulfill stakeholders' needs and wants
- These needs evolve over time, often diverging from the system's original capabilities
- Thus, a system's value to its stakeholders diminishes over time
- Systems can be designed to meet adaptability goals
- Adaptable systems lend themselves to future enhancements to meet evolving stakeholders needs

From Financial to Architecture Options

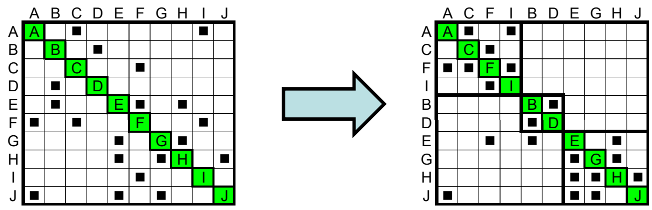
In finance and economics, an "**option**" is "**<u>the right but not the obligation to exercise a feature of a contract at a future date</u>**" (Higham, 2005)



Component-based DSM Approach

1. Decompose the system into its components
2. Document the interactions between the components using a DSM
3. Cluster (integrate) the components into "Modules"

"In partitioning [the system architecture], choose the elements so that they are as independent as possible—i.e., elements with low external complexity and high internal complexity." (Rechtin, 1991)



Rationale for Model

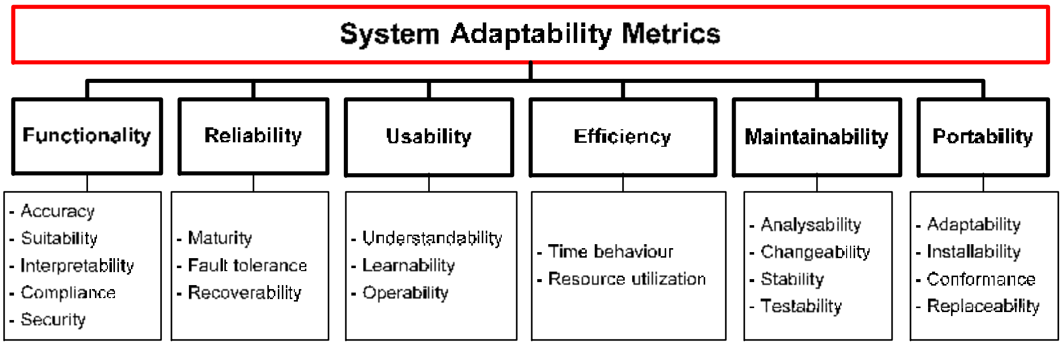
- System modules allow functionality to be isolated within certain groups of components
- Components and modules will evolve at different rates
- Therefore, isolate quickly-changing modules to facilitate their replacement
- Modules thus provide a kind of option for a designer
- More modules imply more options (a benefit)
- However, more modules also imply more inter-module interfaces to manage and control (a cost)
- Therefore, find the right set and number of modules to balance these benefits and costs—i.e., an optimal architecture from a DFA perspective

Three Main Variables in the Model

1. Component Adaptability Factor (CAF)
2. Component Option Value (COV)
3. (Internal and external) component Interface Cost Factors

Metric 1: Component Adaptability Factor (CAF)

- Adapted from software standard
- ISO/IEC 9126-1 (Product quality)



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CAF Sub-Metrics

$$CAF = w_F F + w_R R + w_U U + w_E E + w_M M + w_P P$$

$$\sum_{i=\{F,R,U,E,M,P\}} W_i = 1$$

Metric	Variable	Weight (w_i)
Functionality	F	0.1
Reliability	R	0.1
Usability	U	0.1
Efficiency	E	0.1
Maintainability	M	0.4
Portability	P	0.2

Each of these six sub-metrics is based on further sub-sub-metrics…

Example CAF Computation

Metric	Variable	Sub variable					Variable		CAF
		ID	Name	Weight	Value	Total	Total	Weight	
Functionality	*F*	*F1*	Accuracy	0.2	0.1	0.02	0.30	0.10	0.03
		F2	Suitability	0.2	0.2	0.04			
		F3	Interpretability	0.2	0.3	0.06			
		F4	Compliance	0.2	0.4	0.08			
		F5	Security	0.2	0.5	0.10			
Reliability	*R*	*R1*	Maturity	0.33	0.1	0.03	0.20	0.10	0.02
		R2	Fault tolerance	0.33	0.2	0.07			
		R3	Recoverability	0.33	0.3	0.10			
Usability	*U*	*U1*	Understandability	0.4	0.1	0.04	0.18	0.10	0.02
		U2	Learnability	0.4	0.2	0.08			
		U3	Operability	0.2	0.3	0.06			
Efficiency	*E*	*E1*	Time behavior	0.2	0.1	0.02	0.18	0.10	0.02
		E2	Resource utilization	0.8	0.2	0.16			
Maintainability	*M*	*M1*	Analyzability	0.1	0.1	0.01	0.29	0.40	0.12
		M2	Changeability	0.3	0.2	0.06			
		M3	Stability	0.2	0.3	0.06			
		M4	Testability	0.4	0.4	0.16			
Portability	*P*	*P1*	Adaptability	0.2	0.1	0.02	0.26	0.20	0.05
		P2	Installability	0.3	0.2	0.06			
		P3	Conformance	0.2	0.3	0.06			
		P4	Replaceability	0.3	0.4	0.12			
									0.25

Metric 2: Component Option Value (COV)

By analogy to the Black-Scholes model for financial options:

Financial Options	Symbol	Architecture Options
Current stock price	*S*	The current value of a given system component
Strike price	*X*	The estimated value of the given system component after it was upgraded
Volatility	*σ*	The uncertainty in the lifetime-value of the upgraded component within the system as viewed by stakeholders and translated into market-value over the specified period of time
Time to expiration	*T*	The time to start deployment of the upgraded component within the system
Risk-free interest rate	*r*	Risk-free interest rate associated with funding required to upgrade a given system component at a prescribed schedule of project upgrade
Expected Option Value	*COV*	The expected option value of the given system component

Black-Scholes Formula

$$COV = S\mathrm{N}(d_1) - Xe^{-rT}\mathrm{N}(d_1 - \sigma\sqrt{T})$$

where

$$d_1 = \frac{\ln\left(\frac{S}{X}\right) + \left(r - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}}$$

and $\mathrm{N}(x)$ is the standard normal distribution

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Example-2: Expected Option Value (EOV)

Appropriate experts would need to estimate:

1. The current and future contribution of the component to the overall sales price of the system
2. The uncertainty in the lifetime-value of the upgraded component within the system.
3. The planned time horizon for deploying the upgraded system
4. The prevailing interest rate over the planned time horizon

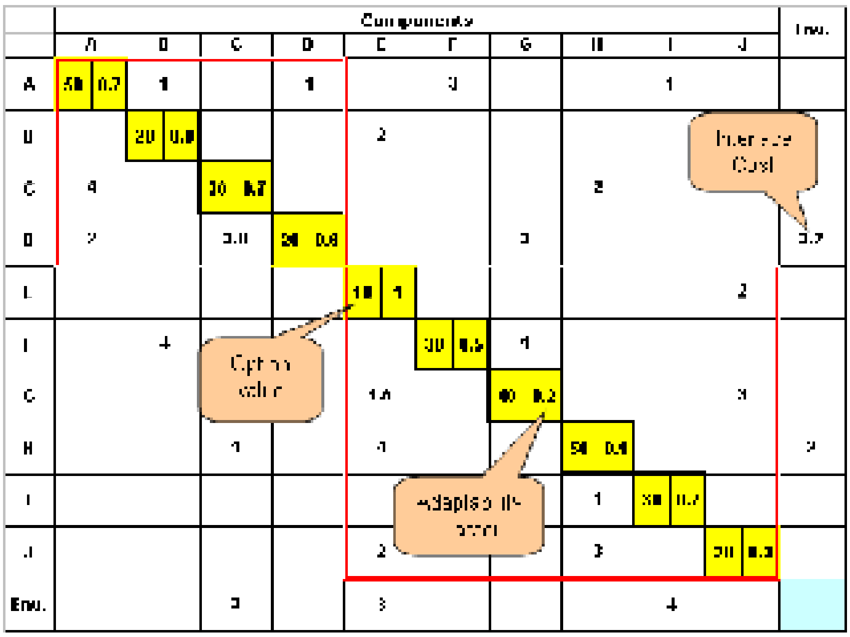
Term	Variable	Example Value
Component current value	S	\$700
Component future value	X	\$1000
Standard deviation of distribution of potential future value	σ	20%
Upgrade horizon	T	3 years
Risk-free interest rate	r	4.0%
Component option value	COV	\$39.80

Metric 3: Interface Cost Factors

Interactions			Range	
Name	**Description**	**Symbol**	**Low**	**High**
Material	Interaction identifies needs for materials exchange between two elements.	*IM*	0.0	1.0
Spatial	Interaction identifies needs for adjacency, force transfer or orientation between two elements.	*IS*	0.0	1.0
Energy	Interaction identifies needs for energy transfer between two elements.	*IE*	0.0	1.0
Information	Interaction identifies needs for information or signal exchange between two elements.	*II*	0.0	1.0

- Overall interface cost is the sum of these four (and/or other interactions) => 0 to 4
- Some types of interactions (e.g., information) may have their maximum lowered to give preference to other types of interactions (e.g., spatial)

Example



Modeling the Adaptability Value of a System Architecture

- One or more components may be combined to create a module
- A large module composed of many components has a lower expected option value than many modules composed of few components
- The expected economic value of a module is related:
  - Positively to an appropriate function of each of *n* components' COVs, each multiplied by its corresponding CAFs
  - Negatively to an appropriate function of the expected costs associated with all (1) internal, inter-module interfaces, $Ii_{n,k}$, and (2) external (module-to-environment) interfaces, $Ie_{n,l}$
- Note that *intra-module* interface costs are ignored in the model
- E.g.: $X_j^{(1)} = \sqrt{\sum_{n=1,2,...}\left(COV_n \times CAF_n\right)^2} - \sum_{n=1,2,...}\left(\sum_{k=1,2,...} Ii_{n,k} + \sum_{l=1,2,...} Ie_{n,l}\right)$

Adaptability Value (AV) of Example

$$X_1^{(1)} =$$
$$\sqrt{(50*.7)^2+(20*.9)^2+(30*.7)^2+(20*.6)^2}$$
$$-(3+1+2+2+3+1+4+3.2+3)=24.0$$

$$X_2^{(1)} =$$
$$\sqrt{(10*1)^2+(30*.5)^2+(40*.2)^2+(50*.1)^2+(30*.7)^2+(20*.3)^2}$$
$$-(4+1+2+4+3+3+1+2+2+3)=4.8$$

$$AV^{(1)} = X_1^{(1)} + X_2^{(1)} = 28.8$$

Merton's Theorem

- This approach aligns with Merton's Theorem (Merton, 1973): For general probability distributions, a "portfolio of options" is more valuable than an "option on a portfolio."
- That is, *the option value of an architecture based on a portfolio of modules is greater than one composed of a single module*
- Thus, the "best architecture" should contain some number of modules that is less than the number of components (or else the interface costs become too high) but also greater than one (because the option value would be too low)

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Conclusions

- The next step is to explore the AVs of alternative architectures, perhaps by using a genetic algorithm, to find *AV**
- The paper provides further thoughts on how to gather the data
- The model provides a starting point for considering the adaptability of a given system architecture
- Optimal architectures from a traditional standpoint may not be optimal once COVs and CAFs are considered
- Future work:
  - Model verification and validation on industrial applications
  - Further development of aspects of the model
  - Exploration and comparison of short- and long-term optima

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