Towards coordination of decentralized embedded system development processes

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1 Introduction

An acceleration in technological change and shorter product life cycles lead among other things to companies’ concentration on their core competencies and to a parallelization of formerly sequential processes. This results in an increasing number of collaborations between firms. This trend can also be observed in research and development, where projects are often conducted corporately by various partners.

An example for such a cooperation is the development of embedded systems. Embedded systems are characterized by a modular design of different interacting hard- and software components. Thereby, the performance of the overall system depends on the interaction of the individual components’ performances. In current system industry’s practice, these components are developed by specialized suppliers and are then combined to the embedded system by a system integrator. Since these partners are usually legally and economically independent companies, the cooperation is regularized by contractual agreements. In practice, fixed-price contracts are most commonly used. In these contracts, components’ requirements as well as prices are fixed ex-ante by the system integrator. However, uncertainties exist with regard to the outcome of the development process. For instance, the performance of components as well as of the overall system cannot be predicted with certainty. Additionally, partners may follow different objectives. Thus, inefficiencies in the design process as well as in the design of the
embedded systems often occur. Some of these uncertainties and inefficiencies might be absorbed by making use of existing substitutional dependencies between components. However, this is not possible when inappropriate contracts as well as insufficient incentive structures are applied, since these lead to a decreasing flexibility in the development process and thus to an increase in development costs. Thereby, economic risk for suppliers and integrators increases. Overcoming these difficulties requires improved coordination of the partners ahead of and during the development process.

Hence, the aim of this contribution is to improve collaborative development processes of embedded systems by adapting mechanisms from supply chain management to development processes. As in supply chain management cooperation is regularized by contracts. In addition, uncertainties exist in the decentralized development processes as in supply chain management, which lead to inefficiencies in the cooperation. Supply chain management has rich experience in flexible contracting with various incentives, targeting overall flexibilization, risk mitigation, and economic fairness [1]. Unlike in supply chain management there are substitutional dependencies between components' attributes in the development process. However, differences between production and development processes currently prevent an easy adoption of these mechanisms. First approaches to the flexibilization of contracts in embedded system development processes are given by [2, 3].

In the following section a mathematical model for cooperative development processes is described and analyzed with regard to the optimal actions of the partners.

2 A model for the development of embedded systems

This section studies coordination in embedded system development processes with one omniscient integrator and two independent suppliers. In the following, we first describe the model. Afterwards we analyze a deterministic case in a centralized as well as in a decentralized setting. In the deterministic case both suppliers can determine the result of their development with certainty. The centralized setting is analyzed first, i.e. how the decision would be taken by one actor developing and integrating both components. Then, the deterministic decentralized setting, i.e. decision making by independent actors, is analyzed with regard to coordination ability of a fixed-price contract. Thereby, the omniscient integrator specifies the parameters of the contract to influence the decisions of the suppliers and thus the result of the development. The model
is then expanded by taking into account uncertainties of one supplier with regard to the attribute of the component. In the stochastic case a centralized setting is analyzed.

2.1 Model description

In this (single-period) model, there are three independent actors, one integrator and two suppliers. The two suppliers each develop one component of an embedded system for the integrator. The operability of the embedded system, and thus the utility of the integrator, depends on the attributes \( a_i \) of the components to be developed, with \( i = 1, 2 \) indicating the two different suppliers. There is a substitutional dependency, with regard to the components’ attributes. The function \( a_2 = s(a_1) \) describes the efficient boundary of combinations of values of the components’ attributes in the interval \([a_{i,\text{min}}, a_{i,\text{max}}]\), for which the overall system is executable. If the system is executable, the utility of the integrator is one, otherwise it is zero. These interdependencies are shown in Figure 1. To model the 0-1-character of the utility function \( n^g_i \) of the integrator \( I \) in a continuously differentiable manner, it is approximated by a three-dimensional Sigmoid-function. To take the substitutional dependency between the two components into account, the Sigmoid-function is adjusted, such that the function \( s(a_2) \) runs exactly through its turning point. This results in the following utility function of the integrator, with \( d \) specifying the slope in the turning point, \( d \to \infty \):

\[
n^g_i(a_1, a_2) = \frac{1}{1 + \exp(d \cdot s(a_1))} \cdot \exp(-d \cdot a_2)
\]

(1)

The results of the development process, as realized values of the components’ attributes, depend on the efforts \( w_i \) of the suppliers. This coherence between effort \( w_i \) and value \( a_i \) can be described by the function \( a_i = k_i(w_i) \). Thus, the utility function of the integrator can be rewritten as follows:

![Fig. 1. Interdependencies between \( a_1 \) and \( a_2 \).](image)
\[ n_i(w_1, w_2) = 1/(1 + \exp(d \cdot s(h_1(w_1))) \cdot \exp(-d \cdot h_2(w_2))) \]  

The development costs depend on the effort \( w_i \) of supplier \( i \) and are described by the function \( c_i(w_i) \).

### 2.2 Model analysis

**Deterministic Case.** In the central setting (\( c \)), one decision maker can control development processes at suppliers as well as the integration. Hence, its aim is to maximize the total profit \( \Pi \) of the development process. This profit results from the utility of the integrator \( n_i^w \) minus the development costs \( c_i \) of the suppliers as follows:

\[ \Pi(w_1, w_2) = n_i^w(w_1, w_2) - c_1(w_1) - c_2(w_2) \]  

The optimal efforts \( w_{i,d}^* \) of the suppliers, that lead to maximized profit of the overall system, result from the analytical determination of the extreme point of this function. In the central setting, these parameters can be set by the central decision maker, i.e. the integrator.

In the decentralized setting (\( d \)), the omniscient integrator determines the parameters of the fixed-price contracts, i.e. the required efforts \( \tilde{w}_i \) of the suppliers. Based on these parameters, the integrator then specifies the transfer payment function determining the amount to be paid by the integrator to the supplier. For a fixed-price contract, an effort of \( w_i < \tilde{w}_i \) results in no payment, while for efforts \( w_i \geq \tilde{w}_i \) the payment corresponds to the development costs \( c_i(\tilde{w}_i) \) (see Figure 2).

![Fig. 2. Fixed-price contract. Fig. 3. Interdependencies between a2 and w2.](image)

To model the 0-1-character of the transfer payment function in a continuously differentiable manner, it is approximated by a Sigmoid-function. The turning point of the Sigmoid-function is described by the required effort \( \tilde{w}_i \). This results in the transfer payment function \( t_i \), where \( m \) specifies the slope in the turning point, \( m \rightarrow \infty \):

\[ t_i(\tilde{w}_i, w_i) = c_i(\tilde{w}_i)/(1 + \exp(m \cdot \tilde{w}_i) \cdot \exp(-m \cdot w_i)) \]
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Since the integrator is omniscient and he wants to maximize his utility, he chooses the required effort $\hat{w}_i$ in accordance to the optimal efforts $w_{i,z}^*$ in the central case. The supplier then determines the effort $w_i$, with which he can maximize his profit $\pi_i$ based on the transfer payments set by the integrator and resulting development costs. The optimal effort $w_{i,d}^*$ of the supplier results from the analytical determination of the extreme point of the following function:

$$\pi_i(w_i) = t_i(\hat{w}_i, w_i) - c_i(w_i)$$

(5)

The analysis shows that the optimal effort in the deterministic decentralized setting with fixed-price contract corresponds to the optimal effort in central planning: $w_{i,d}^* = \hat{w}_i = w_{i,z}^*$.

Interpretation: In the deterministic case, the omniscient integrator is able to set the parameters of the fixed-price contract in a manner, that the operability of the overall system is achieved with minimal costs. Due to the transfer payment structure of the fixed-price contract, suppliers choose exactly the required effort. A higher and thus more costly effort would not be profitable for the suppliers, because the transfer payment does not increase, while a lower effort would result in zero transfer payment. Thus, suppliers choose the effort, which is optimal for the overall development process. This means that the fixed-price contract coordinates the cooperation partners during the development process.

Stochastic Case. In the following, the model is enhanced taking uncertainties with regard to development results of one of the suppliers into account. This is done, replacing the functional relationship $a_i = k_i(w_i)$ between effort $w_i$ and resulting value $a_i$ of the components’ attributes by a stochastic correlation. It is assumed that the probability of a certain value $a_i$ of the component’s attribute is uniformly distributed in the interval $[a_{i,\text{min}}, a_{i,\text{max}}]$. Such a uniform distribution is typical for new developments, where no experiences of similar projects exist and the development outcome is totally uncertain within a certain interval. However, the supplier can still influence the development results with effort $w_i$. Every effort $w_i > 0$ shifts the lower interval limit to the right by $w_i$, so that the existing interval of uncertainty is reduced to the interval $[a_{i,\text{min}} + w_i, a_{i,\text{max}}]$. Thus, an increase in effort shifts the expected value to the right, as can be seen in Figure 3. Optimal efforts of the suppliers from the perspective of a central planner in the stochastic case (s) are calculated integrating the stochastic correlation between effort and value of the component attribute of one supplier (here supplier 2) as follows:
\[ n^W_1(w_1, w_2) = E[n^W_1(w_1, w_2)] = \int_{a_2, \text{min} + w_2}^{a_2, \text{max}} \frac{1}{1 + \exp(d \cdot s_k(w_1)) \cdot \exp(-d \cdot \frac{a_2}{a_2, \text{max} - (a_2, \text{min} + w_2)})} d(a_2) \] (6)

The development costs \( c_t(w_t) \) of the suppliers remain the same. The optimal efforts \( w^*_{t,s} \) of the suppliers result from the analytical determination of the extreme point of the following function:

\[ H_s(w_1, w_2) = n^W_1(w_1, w_2) - c_1(w_1) - c_2(w_2) \] (7)

The analysis shows that the optimal efforts \( w^*_{t,s} \) of suppliers differ from \( w^*_{t,2} \) and lead to an expected combination of components' attributes which is on the right side of the efficient boundary \( a_2 = s(a_1) \) of the deterministic case. Hence, uncertainties with regard to the development results of one supplier can lead to configurations of the overall system, which are overdimensioned and thus inefficient compared to the deterministic case.

3 Conclusion and outlook

In this paper we presented a mathematical model for cooperative development processes of embedded systems. We analyzed a deterministic case in centralized and decentralized setting as well as a stochastic case in centralized setting, each with regard to optimal action of the partners. Future research will concentrate on the decentralized setting in the stochastic case.

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References