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Improving Lead-Time in Product Development

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Abstract

The impact of modular products on the organization of product development has recently attracted interest in academia. This paper explores the economic rational behind the idea that modular products result in modular product organizations using a team-theoretic approach. An important implication that can be drawn from team theory is that the nature of the design problem and the way in which it can efficiently be decomposed into design tasks strongly influence the information structures of organizations and therefore also the extent to which the organization can be characterized as a modular organization. Different economic rationales behind task definitions are identified and discussed. The organization of product development activities also can be expected to vary with the main goal of the product development team. I argue that when the minimization of lead-time is the main goal one should expect to find a more modular product development organization among firms that follow a modular product development strategy compared to those that follow an integral product development strategy.

I. Introduction

A number of authors have argued that modularization of products has profound implications for the organization of product development activities. For example, Ulrich (1995) points out that modular designs change the content and importance of different design phases, and that design teams become more ".. 'supplier-like' in the sense that interaction is structured and relatively infrequent" (Ulrich, 1993,p. 435). Sanchez and Mahoney (1996, p.64) argue that products influence the design of organizations, so that "…modularity in products becomes an important strategy for achieving modularity in organizational designs" and Schilling (2000) points out that [m]odularity within the firm not only enables economies in product design but may also greatly simplify coordination" (p. 320). The argument in this paper centers on precisely the link between product modularization and modularization of product development organizations. The contribution of this paper is to provide an economic rationale for the proposition that modular products result in modular product organizations. In particular, the link between modularization of products, increases in lead-time, and the organization of product development activities is investigated.

Modularization is a product development strategy that is based on a product architecture[1] where different functions of a product are implemented by different and relatively independent physical components whose interfaces are defined by a set of interface standards in a way that allow for substitutability of components (Sanchez and Mahoney, 1996; Garud and Kumaraswamy 1993). This differs from an *integral* design strategy, where each component may implement many functions and where each function is implemented by many different components.[2] The relative independence between components in modular products implies that improvements in one product function have relatively little bearing on other functions.

Modular product development *organizations* are characterized by loosely coupled design activities organized around loosely coupled self-managing teams. These teams are working within the information structure of a modular product architecture, in the sense that directions needed for coordination between these loosely coupled teams are provided by the standardized interface specification of product components. Finally, the development of new technologies and components is decoupled from the development of new product architectures. This creates a distinction between the group of designers (architects) that are responsible for the decomposition of a new product into functional components, and for defining interface specifications and the group of designers that

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[1] An architecture can be defined as "(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components" (Ulrich 1995, p.420).

[2] It should be noted that products are rarely strictly modular or integral. Even in a modular product there may be strong interdependencies between components at the level of detailed design where the implementation of the ancillary functions are to be solved.

work on developing the different components (Sanchez and Mahoney, 1996; Sanchez 2000).

The need for any type of product organization arises with the creation of a large team to match the challenges of large-scale product development. Different forms of organizations can from an economic perspective be attributed to the different aims and constraints that problem solvers face. The complexity and technical interdependencies in the product design may well be one important constraint in forming organizations. [3] Organizations will also be shaped by their purpose. Product development organizations often have to fulfill many purposes such as minimize time spend on the development of a new product, ensure accuracy in fulfilling design specifications, introduce new variants or radically new products that better fulfill customer wants or eases manufacturability. The efficient organizations are those that fulfill their purpose with the best use of the resources devoted to product development. This paper focuses on minimizing lead-time as the primary purpose of the organization. The innovations are assumed to be incremental and the levels of ambition in product development given.

In the product development literature there are suggestions that a link exists between modular product designs and improved lead-time. For example, Cusumano (1997) has pointed out that a modular product development strategy makes it possible to increase lead-time, since modular products reduce the need for iteration between tasks. Moreover, modular products enable a greater use of parallel product developments. [4] This indicates that the link between modular products and lead-time in product development is to be found in the differences in the definition and organization of tasks relative to firms that pursue an integral product development strategy. The question is if the differences that result in an increase in lead-time in the organization of product development tasks are in fact reflected in a more modular product development organization.

Organizations may differ in many respects. This paper focus on how modularization of products may impact on first, the way in which tasks are defined in order to minimize lead-time and second, on the efficient organization of information structures of the organization. The extent to which tasks are defined more narrowly in

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[3] From the contingency theory of organization theory (Lawrence and Lorsch ,1967; Thompson, 1967), we know that different types of technology, and especially differences in the nature of interdependencies between technological tasks are important contingencies in shaping organizations. In the product development literature it has been pointed out that differences in the overall purpose of the product development effort are also likely to give rise to different organizational forms. For example, Fujimoto (1989) has argued that the choice of strategy (volume producer or high–end specialist) shapes organizations. Moreover, Wheelwright and Clark (1992) point out that the organization of product development depends on the degree of novelty in the products.

[4] Many other benefits have been attributed the modular product development strategy as compared to the integral product development strategy. These range from greater mass customization, more easy upgrading of products, less need for market surveys and increased lead-time (Feitzinger and Lee, 1977; Ulrich, 1995; PineII, 1993; Sanchez, 1996). Some of these benefits can be attributed mainly to the design of the product some mainly to the impact of modular product designs on the effective organization of product development activities.

firms that pursue a modular product development strategy is in assessing the link between modularity in products and organizations. This is because most system be it organizations or products at some level are decomposable into relatively independent units (Schilling, 2000). The contribution consists in specifying an economic rational behind the idea that modular products produce modular organizations.

The organization of the discussion of the link between modularization of products, minimizing lead-time and modular product development organizations are organized by answering the following two questions A) In what ways are modular product development strategies likely to alter the organization of product development activities in ways that improve lead-time relative to integral product development strategies? B) Will the organizational principles that maximize lead-time result in modular product organizations?

The paper is structured as follows. Section II ("*Lead-Time and the Organization of Product Development Activities*") clarifies the concept of lead-time and introduces a terminology in which to describe different types of product development activities. Section III ("*The Economic Rationales of Task Definitions*") provides a perspective informed by economics on the benefits of task definition. The definition of tasks and teams is one way of breaking up large-scale problems up into small scale problems that can be managed by small teams with individuals that carry out some preliminary- or well-defined tasks (Cusumano, 1997). The section identifies various principles for defining tasks based on the economic rationales of A) maximizing labor productivity and knowledge production (Smith 1776, Simon, 1985; Cohen and Levinthal, 1990; Nonaka, 1994), and B) economizing on bounded rationality (Simon, 1969, Alexander 1979). In Section IV ("*The Structure of Information Processes*") a team-theoretical approach (Radner, 1992; Casson, 1994; Carter, 1995) is applied to illuminate the issue of the efficient design of information structures that support the experimental activities that may lead to the production of new product concepts or new technological solutions. Section V ("*Conclusions: Implications of Modular Product Designs on Organization in Product Development*") summarizes the analysis with respect to the link between minimizing lead-time and modular organizations.

II. Lead-Time and the Organization of Product Development Activities

In general terms, product development can be seen as consisting of activities such as information collection, information processing, creative thinking and problem solving. The purpose of product development is to create a new product with certain more or less well-defined quality characteristics and functions or to upgrade the quality of an established product. The outcome of such a process is a description of a product concept with a set of technical specifications on how the various functions of the product are to be implemented in the product. The project requirements may vary greatly from project to project. Engineers begin with a broad set of objectives such as the price rage of the product and its functional requirements. Given these characteristics, the effectiveness of project organization depends on the quality of the design, the costs, and on the lead-time.

Lead-time in product development is perceived of as a very important variable in product development (Smith and Reinertsen, 1995; Meyer, 1993). It makes a company able to respond fast to competitors moves in product markets, enables them to adjust fast to new customer requirements, and is also claimed to be a source of competitive advantage over less fast moving competitors. The latter may be grounded in the ability of a firm to earn quasi-rents on novel products because of the loyalty that customers may exhibit toward the first mover (Schmalensee, 1982; Shapiro, 1983 Klemperer, 1987). Lead-time is traditionally measured as the length of time from the initiation of a concept generation to market introduction (Clark, Chew and Fujimoto, 1987). The lead-time of a project depends on the project strategy which include the differentiation and price ambitions of the project, the scope of the project, and the capabilities of engineers. These factors influence the lead-time of each of the development tasks, whereas the project organization influences the overall lead-time. The project organization encompasses such issues as the degree of specialization and the methods of integrating the tasks of individuals, as well as of the pattern of communication between tasks. (Clark, Chew and Fujimoto, 1987).

In the following, I use the terminology adopted by Ulrich and Eppinger (1995) to describe the different types of activities in product development. They characterize the product development process as taking place in five phases, namely 1) concept development, 2) system-level design, 3) detailed design, 4) testing and refinement, and 5) production ramp-up. All of these phases can be described by a number of distinct activities that have to be performed. The purpose of the concept development phase is to generate the product concept for the product. A product concept "... is an approximate description of the technology, working principles, and form of the product" (Ulrich and Eppinger, 1995, p.78). [5] At the system-level of design alternative concepts are evaluated and major sub-systems are defined. The detailed design activities consist of the development of the specific design solutions and the marketing and production planning. In the testing and refinement phases the design solutions and plans are tested and refined and finally executed in the production ramp-up phase. In the following, I shall limit my attention to the concept development, the system level and the detailed design phases, since many of the differences between modular and integral design strategies arise from the different ways of tackling the information processing and problem solving activities in these three phases. This limited focus draws attention to the importance of interdependencies in the product design at the expense of the importance of the interdependencies between product design, production and marketing (Whitney, 1988). This limited focus also implies that the lead-time considered here is the time from concept generation to product design, rather than the time from product initiation to

[5] Ulrich and Eppinger use the word product concept in a different way compared to the general use in the marketing literature where a product concept is considered to be a package of functions that is unique.

market introduction. Important issues such as design for manufacturability that may reduce the overall lead-time is not considered.

Issues such as differences in ambitions of the project and the capability of the engineers are not considered since focus is on the influence of differences in the project organization on lead-time. I shall not discuss the benefits and costs of organizing product development departments in project or functional units (Allen and Hauptman, 1987; Larson and Gobeli, 1988, Clark and Wheelwright, 1992) since, the main focus is on a single product development project rather than on the development of platform technologies and maintenance of technological capabilities across projects. Finally, the impact of outsourcing of development activities is not considered. It is thus assumed that the same types of activities are carried out within the project organization independent of whether a modular or an integral product strategy is pursued.

III. The Economic Rationales of Task Definition

The way in which product development projects are "broken up" and task are defined and allocated to individuals strongly influences the type of coordination problems that come to characterize the development project (von Hippel, 1990; Eppinger, Whitney, Smith and Gebala, 1994). However, task definition is not determined by cost of coordination considerations alone. In fact, coordination considerations are constraints on task definitions rather than the rationale behind task definitions. Some of these constraints may be relaxed by clever designs of information structures. In the following sections, two main reasons for dividing productive activities (including problem solving) into sub-tasks are distinguished. First, task definition may be perceived of as a way of economizing with bounded rationality, and, second, task definition may be perceived of a division of labor in problem solving which may increase labor productivity and knowledge accumulation.

Tasks may loosely be defined as the partitioning of product development activities in ways which delimit more or less precisely the activities that are carried out by one or a group of individuals from those activities that are carried out by another individual or group of individuals[6]. At one extreme, all sub-task delimitation may take place at the very beginning of the product development project; at the other; it may be part of the ongoing process of product development. Furthermore, task delimitation may be performed by the person(s) appointed as responsible for the entire project or it may be allocated to different broadly defined teams (Johne, 1984; Clark and Wheelwright, 1992;

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[6] I distinguish between activities and tasks. Tasks may encompass one or more discrete separable types of activities. It is difficult to pin point what makes activities separable. Some activities clearly cannot be separated for physical reasons. Other activities such as conducting or creating a sculpture may easily be separated into a number of distinct activities. However, it may be difficult to achieve the best result possible if the separable activities are to be carried out as separate tasks. Problems arise because skills or talents cannot be transferred instantly in the form of instructions.

Ludquist, Sundgren and Trygg, 1996). However, the economic principles behind task delimitation remain the same whether a firm follows a centralized or an autonomous model of project management. The following section therefore provides some arguments for delimitation of tasks in product development.

Economizing with Bounded Rationality

The bounded rationality of individuals is one important reason for breaking complex problems up into sub problems that may be allocated to different individuals to be solved (Simon, 1969). One aspect of bounded computational capacity of individuals may be that there are sharply diminishing returns to information processing and problem solving as increased complexity of problem solving increases the load of information processing. Diminishing returns to information processing may show up as inferior solutions or as more than proportional time spent on problem solving. One way of overcoming the problems of diminishing returns is to divide a complex design problem into smaller and less complex problems.[7]

Breaking up design problems is a way of economizing with bounded rationality even if only one person is involved in the problem solving activities (Simon 1969; Radner 1992). However, if different individuals solve different sub-problems, it may be possible to economize even more on bounded rationality and thereby increase lead-time. What sort of heuristics can then be used to define product development tasks in ways that economize the most with bounded rationality? Within the sphere of social systems the solution proposed by Simon (1969) is to construct sub-systems and hierarchies by making a chart of who interact most intensely with each other. Then, Simon explains, "… the clusters of dense interaction in the chart will identify a rather well defined hierarchic structure" (ibid., p. 88). The underlying assumption is that task definitions, which economize on bounded rationality, are the ones that solve some of the coordination problems by reducing the need for communication the most.

In the context of product design, Eppinger, Withney, Smith and Gebala (1994) have suggested a similar approach. However, they also emphasize that there is link between the type of technological interdependencies that designers encounter in the product design and the pattern of interaction between designers. Based on various case studies, they find that iterations between product development tasks are reduced most when tasks are defined on the basis of a chart of the interaction between the design parameters specified by the designers.[8] Von Hippel (1990) has illustrated this point very well in an example of the development of an airplane, where the product development problem is

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[7] Complex in the sense that it is ".. made up of a large number of parts that interact in a non simple way" (Simon, 1969, p.86).

[8] Eppinger, Withney, Smith and Gebala (1994) mention other factors beside information exchanges may also be of importance in defining tasks, for example, task duration and the degree of dependence with respect to "...task communication time, functional coupling, physical adjacency, electrical or vibration characteristics, parameter sensitivity, historical variance of task results, certainty of planning estimates, or the volume of information transfer" (p.4). These factors are particularly important when firms have a fixed number of designers employed in the organization.

subdivided in two different ways into two meta-tasks. In the first case one sub-problem consists of developing the rear end and the other sub-problem consists of developing the front end of the plane whereas in the second case one sub-problem is to develop the engine and the other to develop the aircraft body. If the design of the rear and front part is allocated to different teams, each team has to be fully informed *about many more design variables* than if the design of the body is allocated to one team and the design of the engine to the other team. Moreover, in cases where designers' knowledge of interdependencies between sub-problems are incomplete, task division in accordance with the first example most likely would imply many iterations between problem definition, target specifications and problem solving tasks in detailed design as the two design teams discover incompatibilities in their solutions.[9]

To sum up, in order to reap benefits of economizing on bounded rationality and reduce information processing time, task partitioning is often necessary. In specifying tasks, one needs to consider how to reduce the amount of information each person needs to receive and communicate and how to reduce the amount of design variables each person needs to be aware of. A first approximation to the problem of defining tasks is to decompose the design problem into relatively independent problems, so that for each sub task one only needs to discover interactions between a limited number of design variables. When many of the interdependencies between design variables are well known, the product development problems can be decomposed into the development of relatively independent components within limits set by interface specifications.

However, some decomposition of design problems may be beneficial even without full understanding of the nature of interdependencies between problems and therefore also of the nature of interdependencies in product design. Schaefer (1999) argues that in a product with complementarities between all design variables, an arbitrary decomposition of the design problem into elements is a way of increasing the understanding of the complementarities. If the product development problem is partitioned in an arbitrary manner into sub problems, the project development group can perform a sort of controlled experiment by solving some sub-problems and trace the effects of the changes on the working of all other sub-problems. Such a "preliminary modularization" of products is an effective way of reducing the time of experimentation needed to achieve an understanding of interdependencies between design variables.

The extent to which iterative processes in product development can be eliminated depends on the nature of the design problem, the product knowledge and how this has been decomposed.[10] Firms that pursue a highly modular product development strategy and have well-specified product architecture have the opportunity to decompose design problems differently from firms that follow a highly integral product development strategy. In a modular product each product function is implemented in the product by relatively independents components. For most incremental improvements of functions

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[9] Another indication of a difference between the two approaches is that it is much easier to reach an optimal design with the second approach than with the first approach.

[10] It of course also depends on whether one wants an optimal design or not.

the important interdependencies between design variables to be explored are likely to be concentrated within components rather than between components. *This implies that a definition of design tasks in accordance with the components that have to be developed most likely will be the one, which reduces the need for iteration and the need for information about design variables most.* This strategy for defining tasks not only reduces the burden on problem solvers' rationality; it also reduces lead-time since time consuming communication is reduced.

Labor Productivity and Knowledge Creation

Another important reason for the partitioning of product development activities into tasks rests in the kinds of gains from labor specialization that were emphasized by Adam Smith (1776). From Smith we know that specialization in production is one of the main sources of improvements in labor productivity in tasks. This implies that an increase in the division of labor may contribute to a reduction in lead-time in individual tasks. Smith ascribes productivity gains to improvements in workers' skills, in time that is saved from avoiding having to switch from one task to another, and in labor saving innovations.

In product development almost all activities have some element of skill. For example, designers use heuristics and technical insight for decomposing design problems or for searching for conceptual solutions. Skills may also consist in the ability to engage in creative processes when trying to conceptualizing new types of solutions or the care and accuracy with which the problem solvers design and conduct experiments or use simulation models. Repetition of the same types of activities over and over is the key to accumulation of all these diverse skills and insights. To increase the rate of accumulation of skills, tasks will have to be defined around activities, which can be repeated by solving the same type of problems. This criterion for task definition may also lead to a reduction of "switching costs" and an increase in "innovativeness." In product development "switching costs" may arise when it takes time for an individual to change his mindset in order to perform a different type of activity. Such switching costs may, for example, arise if one has to switch between market analysis activities and concept development activities or even if one has to switch between the development of different types of components.

Judging from studies in the area of cognitive and behavioral science it seems that there is a rather complex relationship between increasing division of labor and innovativeness (Cohen and Levinthal, 1990). Innovativeness in problem solving can be described as the ability of an individual "... to retrieve a potentially useful piece of information from one's memory and then adapting that information to the problem in hand" (Ulrich and Eppinger 1995, p.88) – or, put somewhat differently, to recombine knowledge in new ways (as in the Schumpeterian notion of innovations).

Bower, Langely and Simon (1983) and Simon (1985) argue that the possession of relevant knowledge and skills is what give rise to creative associations and innovation. Much of the knowledge that is needed is cumulative in the sense that knowledge of prior advances within a field is necessary in order to assimilate information on new advances.

In such cases the rate at which new knowledge can be accumulated increases with the stock of existing knowledge (Cohen and Levinthal 1990).

The building of innovative capabilities seems to be subject to a trade-off between accumulating a certain depth of knowledge and accumulating a certain width of knowledge. On the one hand innovativness requires a certain "[i]ntensity of effort" and "..important aspects of learning how to solve problems are build up over many practice trails on related problems" (Cohen and Levinthal, 1990, p.131). Moreover, in order for boundedly rational individuals to learn effectively from experience the complexity of the problems they solve will often have to be reduced by a decomposition of the problem and a rather narrow definition of the problem solving tasks (Levinthal and March, 1993). These factors call for a rather narrow definition of tasks On the other hand, a certain width of knowledge and therefore width in task definitions may also be important with respect to facilitating innovativeness. Cohen and Levinthal (1990) point out that "… in settings in which there is uncertainty about the knowledge domains from which potentially useful information may emerge, a diverse background provide a more robust basis for learning because it increases the prospect that incoming information will relate to what is already known (p.131). This problem could be remedied in organizations by employing experts of diverse background. However, if these experts posses only highly specialized knowledge, they may be unable to communicate with specialist in other sub-fields.

In fact the creation of new knowledge often requires interaction between different knowledge elements of which some are explicit and other tacit. However, different means of facilitating communication between specialist in sub-fields have been identified by Nonaka (1994). According to Nonaka, knowledge contains explicit as well as tacit elements (Polanyi 1962, 1967). Tacit knowledge involves both cognitive and technical elements. The cognitive elements consist of mental models of the world including schemata; paradigms, beliefs and viewpoints that help the individual interpret the world. The technical elements consist of concrete know-how, crafts and skills that apply to a specific context.

Interaction between knowledge elements may come about in four different ways. Transfer of information is the efficient means when explicit bodies of knowledge are to be brought in contact while social interaction in, for example, teams is necessary if tacit elements are to be exchanged. Moreover, tacit knowledge may be converted to explicit knowledge in a process of externalization in which metaphors and actions play an important role and explicit knowledge may be converted into tacit knowledge through more traditional types of learning. This implies that although the division of labor may create specialist knowledge containing tacit and explicit elements, these may be brought into contacts through various interaction processes of which some require overlapping activities and close interaction.

To sum up, in order to enhance innovativeness four requirements are important to consider when defining tasks. First, some repetition or intensity of effort in the performance of the tasks is important. Second, there have to be some relatedness between the types of problems that are to be solved in terms of the bodies of knowledge. Third, the complexity of the problem has to be manageable to individuals. Fourth when there are great uncertainty with respect to what kind of knowledge is useful for problem solving knowledge accumulation have to be more extensive and tasks may have to be defined more broadly. Finally, the width of the tasks depend on the extent to which it is possible to set up various knowledge transfer mechanisms to facilitate the communication between specialist with different tacit knowledge.

In product development both the technical and cognitive aspects of tacit knowledge may play an important role in many phases in the product development process since much of the knowledge that underlie what we ordinary refer to as skills is tacit. For example, designers may posses certain skills in concept generation and in the design and execution of experiments needed to test technical solutions. The cognitive elements of tacit knowledge may create problems of communicating between specialist in area such as marketing, product design, and production functions. However, some of these costs of specialization may be overcome by the creation of knowledge transfer mechanism such as close links or overlapping teams in product development. In fact, the importance of knowledge sharing as a way of enhancing communication between specialists may explain the many recommendation of establishing close links between for example marketing and design or design and manufacturing (Clark and Fujimoto, 1987, Larson and Goblei, 1988, Clark and Wheelwright, 1992).

The importance of overlapping tacit knowledge between specialists might also explain difference in the size of teams. Schaefer (1999) has argued that low inter team communication cost will result in small and many teams whereas low costs of intra team communication will result in large teams at the expense of the benefits of division of labor. Low inter team communication costs may be attributed to relative few knowledge interdependencies between problems solving activities and low intra team communication costs to well established overlaps in the knowledge domains of specialists.

Modular and integral product development strategies require different types of knowledge accumulation in order to minimize lead-time. Sanchez (2000) points out that with integral product development strategies designers typically try to develop new technologies and new product at the same time whereas with modular product development strategies designers learning about "new technologies, new architectures and new components are intentionally decoupled" (p. 11).

This difference in the need for knowledge accumulation has implications for the way in which tasks may be defined in order to enhance effective innovativness. First, with an integral product development strategy there is much more uncertainty as to what information is relevant for effective problem solving and innovativness. This implies a wider definition of tasks or a wider definition of teams to create greater overlap in knowledge domains compared to that required of a firm pursuing a modular product development strategy. Second, with a modular product development strategy and a well defined product architecture much of the uncertainty in problem solving is confined to the development of the individual components, which imply a definition of tasks in accordance with the development of components. By defining tasks very narrowly around components one may increase the rate of accumulation of component specific knowledge.

However, component development may require many different types of knowledge and this may create a need for a further specialization in work tasks in order to ensure efficient accumulation of the diverse bodies of knowledge. This gives rise to a need for communication and coordination between individuals working on a component development project. One way of ensuring the transfer of tacit knowledge is to have overlapping activities another is the use of a project manager who follows the project through some of the phases and accumulate much of the tacit knowledge about the project. [11]

In the long run accumulation of component specific knowledge may be at the expense of the accumulation of architectural knowledge about ways in which components are integrated and linked together or the accumulation of the kind of deep knowledge of core design concepts and their implementation, which is required for radical innovations (Henderson and Clark 1990). Thus, firm pursuing modular product development strategies cannot in the long run completely avoid the need for overlapping tasks (teams) and will thus also have to expend some of the benefits of labor specialization in order to create innovativeness in architectural designs.

Finally, both firms that pursue integral and modular product development strategies may be faced with a trade-off between accumulation of component/product specific knowledge and accumulation of technical expertise within sub-fields such as various product technologies, marketing, production etc. This trade-off is often recognized in the debate concerning the functional organization of product development contra the project organization of product development (Weelwright and Clark, 1992). However, with modular product development strategies there is a certain probability that there is an overlap between specialization in component knowledge and specialization in sub fields within product technologies. *Thus, in at least the short run a modular product development strategy makes it possible to improve knowledge accumulation in ways that improve lead-time by defining tasks accordance with components.*

IV. The Structure of Information Processes

One important constraint on task definition in product development is the costs of coordinating individual tasks. The economic meaning of coordination is to ensure that given resources are used in their best given alternative uses. However, the sub-division

[11] Clark and Weelwright (1992) have identified three different types of team structures in which project manager are used. These are lightweight, heavyweight and autonomous team structures. These teams vary among other thing in the role and responsibility ascribed to project managers but they have in common the idea that a certain project manager is assigned to the project for at least some parts of the development process.

of a design problem and definition of tasks introduces obstacles to the achievement of coordination since different individuals will come to poses different information about for example customer preferences, technical solutions, critical interdependencies between design variables etc. Thus, efficient information structures need to be designed in order to overcome the problems that such dispersed information and knowledge introduces. Informational structures may be defined as the kind of procedures that are implemented in order to ensure proper communication of information between tasks.[12]

This section discusses information structures in product development from a team-theoretical information processing perspective on organizations. From this perspective the efficient information structures with the efficient allocation of decision rights among product development tasks (or teams) is the one that economize with information processing costs while allowing members of the organization to take advantage of specialization in decision making. Information processing costs may, for example, consist of the costs of transmitting information, costs of investing in information channels, cost due to error in communication or costs of obtaining information through investigations (Carter, 1995; Casson, 1994; Marschak and Radner, 1977). Many of these costs may be interpreted as time spent on the obtaining and transfer of information or time spend on correction of errors in decision making due to faulty communications. The team-theoretical perspective therefore provides a basis on which to identify costs saving information structures of modular and integral product development strategies that may lead to decreased lead-time in product development. In the analysis of efficient information structures the standard team theoretical simplifying assumption of incentive compatibility are assumed to apply

The nature of the design problem and the way in which it is decomposed play an important role with respect to determining the design of information structures since interdependencies in problems solving define the need for communication between tasks. Two characteristics of the decomposed problems are important for the structuring of the information-processing network. The first important characteristic is the extent to which a problem is characterized by what Casson (1994) refers to as "*decisiveness*" and the second important characteristic is the extent to which a problem is characterized by what Radner (1992) refers to as "*associative operations*". The first characteristic refers to the extent to which sequential interdependencies characterize information processing, so that coordination between information processing activities are needed. The latter characteristics refers to a situation, where some of the information processing activities can be carried out independently of other information processing activities. The need for coordination of the information processing activities arises if the individual pieces of information needs to be synthesized in order to reach some sort of decision. [13]

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[12] Galvin (1999) points out that in connections with product modularity the term information structure is often used to denote only the type of product design information that is captured in what Baldwin and Clark (1997) call visible design rules. In team theory the term information structure is used in a broader sense to cover the entire spectra of information required for decision making.

[13] It should be noted that the logical structure of problems which gives rise to natural decisiveness is different from that which gives rise to associative processes. Decisiveness and associative processes do

In the following sections, I argue that with a modular product development strategy the design problem has consciously been transformed into a problem that allow for the minimization of lead time by means of an extensive use of specialization in tasks and the implementation of rather simple and not very time consuming information structures of communication.

Decisiveness, Lead-time and the Definition of Information Structures

When a design problem is broken down into sub-problems the solution to each sub- problem may be conditional on the solution of other sub-problems and important information may be lost when tasks are narrowly defined around sub-problems. For example, it may sometimes be important for designers of complementary components to know how a certain solution concept reacts to changes in test conditions rather than just to know that this solution concept has been chosen. As pointed out by Sanchez and Mahoney (1996), "… information and assumptions underlying upstream design decisions may not be transferred intact to downstream stages of development. Technical incompatibilities between interdependent components may then actually be 'designed into' downstream components" (p. 69).

One important aspect of decision problems is the extent to which these are characterized by *decisiveness* with respect to the communication of information (Casson 1994). Decisiveness is the key to whether or not individuals will share information in some sort of consultation or not: "... [d]ifferences in decisiveness mean that some problems have a logical structure which supports solutions without consultation and some do not" (ibid. p.50). Natural decisiveness occurs when there is a serial interdependence (Eppinger et al. 1994) between two decision takers. Moreover, decision taker B´s can solve his problem equally well by substituting knowledge about the premises for the decision reached by decision taker A with information about the decision he has reached. This is important when the premises for the decision is more costly to transmit than information about the decision that has been reached. For example, the concept generation process and the detailed design are characterized by decisiveness when the choice of a product concept can be carried out on the basis of information about customer preferences alone independent of information about the constraint set by knowledge about product technologies and design solutions. Moreover, the team that works on the system level design only needs information about the concept chosen in order to fulfil their obligations they need not have information about the actual customer requirements. If concept generation and detailed design require market information as well as information about technological factors there is no decisiveness since neither decision can be taken without knowledge of the factors that affect the other decision. [14]

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not preclude one another. In the case of associative processes there are no logical sequence to follow. However, the communication will be structured by the way in which one has chosen to organize problem solving into an efficient hierarchical network (Radner, 1992).

[14] One problem not dealt with here stem from the fact that often product developers do not know that they posses information that is valuable to other product developers. This creates what Hoopes and

Decisiveness is an important consideration in the design of information structures when some information is costly to transmit as may be the case when there is sticky information in design (von Hippel, 1994). Ulrich and Eppinger (1995) provide a fine example from the development of a fork for a mountain bike, where sticky information played an important role. The team who performed the market analysis identified customer needs as "easy to install". For the team that performed the translation of customers needs into target specification this was a too ambiguous statement, since it could be translated into a number of different technical specifications, such as "time to assembly" or "assembled by use of simple tools and simple movements". Such types of sticky information may cause errors in decision taking. More generally sticky information refers to the situation where costs of transferring information is high due to the way in which it is encoded or due to the lack of "absorptive capacity" of receivers of the information, for example, because they lack an understanding of the context in which the information is derived.

Errors in communication (Carter, 1995) is another source of costs of communication. Errors in communication can, for example, be interpreted as a small probability that the wrong decision premises are communicated or because tacit information is incorrectly encoded into memos, plans or interface standards.

An example (based on Casson 1994) may serve to illustrate the implication of decisiveness on the design of information structures. Assume that in a product development project one of two product concepts and one of two technological solutions have to be chosen. The optimization problem of concept selection and selection of technological solutions consists of selecting the concept and technological solution that under conditions **A** (customer preferences) and **B** (state of technological knowledge available to designers) generates the greatest revenue to the firm.

A represents customer preferences which can be of two kinds and a_1 and a_2. The two concepts that can be selected are a_x and a_y. **B** represents states of technological knowledge available to designers that can either b_1 and b_2. Designers can select either of two technological solutions b_x or b_y. The maximum price that concept a_x can generate is P_0 if customer preferences are a_1 while the maximum price that concept a_y can generate under the same conditions is $2P_1$ where $P_0 > P_1$. However, if customer preference are of the kind a_2 the maximum price rise with r for both concepts. The costs of using technical solution b_x or b_y depend on the concept chosen and on the state of technological knowledge b_1 and b_2. With concept a_x the costs of development of technical solution b_x is c_0 when $b=b_1$ while with concept a_y it becomes $2c_0$. The costs of development of technical solution b_y is c1+f1 +f2 with concept a_x and technological knowledge $b=b_1$ and twice as much with concept a_y. However, if

Postrel (1999) term "glitches" which are costly mistakes or costly duplications of work. According to Hoopes and Postrel such costs can be avoided though information integration mechanisms such as overlapping team activities. This is because those who posses valuable information is likely to discover the need for communicating it to the relevant decision takers. This implies that in the choice of efficient information structure managers must take into account their ignorance of who poses what kind of valuable information.

technological knowledge $b=b_2$ the costs are reduced with f_2 independent of concept chosen. Table 1 specifies the revenue functions for different choices of product concepts and technological solutions in different states of customer preference and technological knowledge.

XXXXXXXX *Insert Table 1 Here* XXXXXXXX

The extent to which there is decisiveness depends on the parameters of the revenue functions. As the problem is specified above decisiveness occurs, for example if r>1.25 or r> .75+f2 or if f1 is zero and r>. 25 (Casson, 1994). Under these conditions customer preferences are always decisive for the choice of concept and for the choice of technology. This implies that the team engaged in the selection of concepts can make a decision without information about the state of technological knowledge. Moreover, they only need to communicate their choice of concept in order for the team engaged in specific design to select the technology on the basis of their investigation of the state of technological knowledge.

In Table 2 an asterisk indicates the optimal choices of concepts and technology when customer preferences are decisive and the decision problem is characterized by the following parameter values: p0=4; p1=3; r=1; c0=3.25; c1=2,25; f1=0 and f2=1.5.

XXXXXXXX *Insert Table 2 Here* XXXXXXXX

In Table 3 an asterisk indicates the optimal choices of concepts and technology when three is no decisiveness and the decision problem is characterized by the following parameter values: p0=4; p1=3; r=1; c0=3.25; c1=2.25; f1=1,5 and f2=1.5.

XXXXXXXX *Insert Table 3 Here* XXXXXXXX

The various information structures between marketing and design can be summarized into seven types of structures (Casson, 1994 and Carter, 1995). They are: centralized or pooled, marketing- or design-led, marketing- or design-dominated, or routine decisions. With pooled or centralized information structures all available information about customer preference and technological knowledge is used in making the decision. With the centralized structure information about states and available options in terms of concepts and technological solutions are communicated to a central decision taker, whereas in the case of pooled information this information is communicated between the marketing and the design team. When information structures are marketing-led, the marketing team investigates customer requirements and makes a decision about what concept to choose. They communicate their decision to the design team who investigates the technological knowledge available and make a decision on the basis of their knowledge of the decision of the marketing team and their investigation. With a design-led structure, the order of communication is reversed. In the case of a marketing-dominated structure, marketing investigates customer preferences and makes a decision about the concept. This is communicated to the design team who makes a decision about the technical solution to implement without making inquiry into the state of technological knowledge. Routine decisions occur if one dispenses with investigation of both states.

The problem of selecting an optimal information interface between marketing and design depends on: a) the costs of communicating information between the two activities relative to that of communicating to a central decision taker; b) the costs of investigating the relevant states (**A** and **B**), and; c) the losses in terms of wrong decisions due to suppression of information about states and choices of concepts.

Decisiveness implies that when there is no communication costs and investigation costs, the optimal design of the information structure may be one of marketing or design led decision taking (depending on the nature of decisiveness). These information structures imply a batch communication (Wheelwright and Clark, 1992) between marketing and design with the two tasks being performed sequentially since information about the decision reached by the team with the decisive decision has to be transmitted before the other team can make their decision.

In cases where there is no decisiveness the optimal information structures are either consultative (overlapping teams) or centralized with the communication of decision premises to a central decision taker. Communication may be sequential or instantaneous, depending on the extent to which some overlap in knowledge creation is required for the effective transfer of tacit or sticky information. Intensive communication (Wheelwright and Clark, 1992) may, for example, be needed so that designers may have to be engaged in interpreting marketing information or marketing may have to investigating technological knowledge.

Decisiveness can sometimes be *imposed* on problems by dispensing with the communication of the decision premises. Extensive consultation may then be substituted for sequential decision taking resulting in either marketing or a design led information structures (depending of the costs of communicating either customer preferences or technological knowledge)[15]. Imposing decisiveness on a problems may be efficient if only one party hold information that is highly likely to be decisive or if the consequences of an incorrect decision are perceived of as small relative to the costs of communicating all the relevant information.

Of the two types of information structures the design led is only more efficient (with the given decision parameters of the non-decisive decision problem) if the costs of communicating design plans to marketing are much lower than the reversed type

[15] Sequential decision-taking requires that the knowledge that has to be transferred is not tacit or sticky in the sense that common experience is required in order to interpret the information.

of communication. However, communication costs can be reduced by making one of the states the normal state so that communication only takes place if investigation reveal the unusual state. For example, in the case where there are no- natural decisiveness (table2) the states $a=a_2$ or $b=b_2$ may be made the natural states. If the unusual states occur decisions will have to be made in a consultative manner. Which of the states that are to be made the natural state depends on the probability of its occurrence. Another means of reducing information-processing costs is to dispense with investigations of the decision premises. This may be efficient if an investigation of decision premises (the states) is very costly relative to the expected benefit on the quality of decisions.

As mentioned earlier the efficient information structure in product development depends on the nature of the design problem and the information processing costs. In relation to the design of efficient information structures an important difference between modular and integral product development stem from the fact that with a modular product development strategy the architecture and the interface specification of the product is determined independently of the development of the specific technological solutions that implement the various product functions.

This implies that the choice of architecture is made decisive for the choice of the specific design solutions. In fact, one may interpret the establishment of a product architecture that spans several generations of products as a way of making this architecture the natural state which is to be taken for granted in the choice of the specific design solutions. Moreover, the specification of stable interface standards for components in ways that eliminated interactions between the specific design solutions may be interpreted as a way of eliminating the need for investigations of "states " by the designers engaged in developing these solutions. Interface specifications simply eliminate changes in the decision premises caused by interdependencies between design solutions. If interface standards "freezes states" it creates independence between problems in a way that makes it possible to solve problems concurrently. One way communication, elimination of investigations of states, and concurrent design are all means of reducing lead-time relative to problem solving that require extensive consultation.

However, with integral product designs it may also be possible to carry out some of the detailed design activities concurrently. The information structures characterized as marketing dominated, design dominated or routine makes it possible to engage in concurrent design activities. With these information structures states are either not investigated at all or only one state is investigated. This is efficient if costs of investigation are higher than the expected outcome of investigation and that may very well be the case for some design decisions. Moreover, the costs of making the wrong decisions in detailed design may be reduced if tasks are made only partially concurrent. The "downstream" team then can make an early involvement in the decisions of the upstream team in order to better predict the choice of solution (Wheelwright and Clark, 1992).

Associative Operations, Lead-Time and Parallel Information Processing

A special case of concurrency in design activities is the use of parallel information processing. Information processing often is a time consuming activity which imply that lead-time may be improved if it is possible to economize on the time spend on information processing. Some of the information processing in product development has to do with search for alternative concepts and solutions to specific problems. In these processes there are time to be saved with the introduction of parallel problem solving.

Parallel problem solving requires that the problem to be solved in its entirety have to be characterized by what Radner (1992) calls "*associative operations*". With associative operations the sequence in which the sub-operations are carried out do not matter to the entire result. Linear information transformation and pattern matching are the two paradigm cases of associative operations. Linear transformation takes place when a set of information is transformed into another set of information by the use of some sort of algorithm of transformation. Computing the value of 100 kilo gold from US $ into Singapore $ is an example of transformation by means of a linear decision rule. An example from product development is the transformation of customer statements into target specification. Most likely it is not possible to specify explicitly how this transformation is to be performed but individuals with the same education and experience may employ some of the same tacit heuristics in performing this activity. Thus, it may be possible to allocate this type of activity to different individuals with the same education and have them perform the translation in parallel.

Pattern matching takes place when a sets of data is compare with a reference set of date in order to find the closest match. An example of this may the comparison of dimensions of many different design solutions to a specific design problem in order to find the one that matches a set of specifications. Linear transformations and pattern matching activities makes it possible to organize information processing in a hierarchical manner by defining tasks so that groups of individuals compare sub-sets of solutions and each find the best solutions to the sub-sets problems. Sub-problems are synthesized by sequentially eliminating or transforming sub-solutions until a final solution is arrived at. The implementation of such a hierarchical information processing structure may be a time saving strategy if there are many solutions to be evaluated.

However, there are limits to the hierarchy because delays in problem solving occurs when problems have to move up the hierarchy of information processing tasks because at the apex of the hierarchy capacity cannot be expanded by adding more individuals to perform this activity. An efficient problem-solving network is one where there is an optimal tradeoff between serial and parallel processing. If problem solving is not an ongoing process and if idle capacity represents no costs this is achieved when for a given amount of information "… the number of processors cannot be decreased without increasing the delay, or vice versa" (Radner, 1992, p. 1395). When information arrive continually one can typically reduce delay time by expanding the network as compared to the optimal one shot problem-solving network.

Diminishing returns to parallel problem solving may also occur when product development managers contemplate a parallel team strategy as a mean of gathering information about solutions to a design problem[16]. As argued by Nelson (1959) the costs of using several teams during the initial stage of design is small relative to the benefits that may accrue from the information gathering. However, increases in teams add costs in a linear fashion while the probability of discovering a better solution increases in a hyperbolic fashion moving asymptotic toward 1 this determine an upper bound on the efficient number of teams (Arditti and Levy, 1980)[17].

In general a more intensive use of parallel transformation and pattern matching contributes to the minimization of lead-time by reducing information-processing time. Modular product development strategies are likely to exhibit greater possibilities for implementing hierarchical information processing strategies due to independence between component design solutions.

V. Conclusion: Implications of Modular Product Designs on Organizations in Product Development

The main purpose of this paper has been to provide an economic rationale behind the proposition that modular products result in modular product organizations. An assumption behind this proposition is that modular organizations are efficient means of coordinating product development activities for firms that pursue modular product development strategies. However, the efficiency of one type of organization compared to other types of organizations are not easily assessed unless one considers the aim of the organization and the constraints facing members of the organization in reaching the aim. In this paper I have taken the minimization of lead-time in product development to be the primary aim of the organization and the interdependencies in product designs along with costs of communication to be the main constraints facing product designers.

The analysis of the link between modularization in products, lead-time, and modularization of organizations has been pursued in two steps. The first, step was to investigate how modularization of products influences the efficient definition of tasks and information structures. The second step will be to investigate whether the efficient definition of tasks and information structures result in what some writers in the area of new product development have termed modular organizations.

The previous sections have analyzed the link between minimization of lead-time in product development and the organization of product development activities. Based on this analysis it seems reasonable to assume that organizations pursuing a goal of

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[16] Parallel information processing may also be employed as a way of creating more variety in solutions since the variation in the suggestions of design solutions may increase by having different individuals engaged in the transformation processes.

[17]Based on a study of two different design projects Marples (1961) finds that parallel search for design solutions are most likely to occur when organizations have sufficient manpower and when the problem is not felt to be so difficult that a number of feasible solutions seems improbable.

improving lead-time will exhibit differences with respect to definitions of tasks and information structures depending on whether their product development strategy is an integral or a modular product development strategy. Moreover, the differences in the organization of product development stem from the differences in the interdependencies between design decisions.

I have argued that with respect to the definition of tasks modular product development strategies are likely to produce organizations in which the tasks of detailed design are likely to be rather narrowly defined in accordance with the relatively independent components that implements the various product functions. This definition will improve lead-time by economizing on bounded rationality as well as by improving the rate of accumulation of skills and innovativeness with respect to various product functions. For firms pursuing an integral product development strategy the efficient task definition is much harder to predict, since interdependencies in design decisions will differ depending on the specific product to be developed. However, it seems reasonable to conclude that a much greater interdependence between tasks is likely to persist no matter how tasks are defined. Moreover, there is likely to be more uncertainty with respect to the type of knowledge that is needed to solve design problems. This implies that tasks are likely to be defined in a less narrow manner.

The organization of the information structure that improves lead-time the most is one that makes use of the least amount of communication between tasks in order to ensure coordination between tasks, while at the same time maximizes the gains from a division of labor in problems-solving and information processing. With a modular product development strategy it is likely that firms may make greater use of a kind of information structure labeled "routine" (Carter, 1995) compared to firms pursuing integral product development strategies. This information structure is likely to be efficient with respect to the organization of much of the detailed design activities because the information that the designers need are embodied in the interface standards that are defined as part of the product architecture. With integral product development strategies there will be a much greater need for investigation of decision premises and communication of information between the tasks that make up the detailed design activities so that more investigation and communication intensive information structures are the efficient choice. However, communication costs can be saved to the extent that some detailed decisions are characterized by decisiveness.

With a modular product development strategy the organization of the information exchange between concept generation activities and detailed design are also likely to differ from that pursued with an integral product development strategy. This is because with a modular product the architecture of the product is decided before the detailed design activities begin whereas with the integral product development process the architecture emerge from the solutions to the detailed design problems. The modular product development strategy therefore should provide greater opportunities for imposing decisiveness on the decisions that link concept development, system level design and detailed design activities.

Finally, with a modular product development strategy a much more extended use of parallel information processing is likely to be an efficient way of minimizing lead-time. In particular, firms pursuing integral and modular product development strategies are likely to differ with respect to the use of concurrent design activities in the detailed design. However, with integral design strategies some concurrency in the design activities can be accomplished by having partly overlapping tasks since this may allow the "downstream" designers to better predict the outcome of the "up stream" design activities before these are finalized.

To sum up, firms that pursue a modular product development strategy may minimize lead time with more narrowly defined product development tasks and with the implementation of information structures that rely on less information gathering, greater independence in decision taking and more parallel information processing compared to firm that pursue integral product development strategies.

From the above analysis it seems reasonable to characterize the organization that emerge with modular product development strategies to be modular organizations at least with respect to the organization of incremental innovations. The rather loose coupling of design activities could be expected to result in an extended specialization across firms and Brusoni and Prencipe (2001) have observed the emergence of such patterns of specialization is among producers of aircraft engines and of chemical plants.

The literature on modularity also claims that the development of new components will be decoupled from the development of new product architectures. The analysis pursued in this paper has not systematically taken into account the nature of the knowledge and information interdependencies between architectural innovations and modular innovations in components. But it is likely that architectural innovations may require an organization in which tasks and information structures are at least temporarily redefined in manners that make the organization less modular in order to facilitate trail and error learning processes and cross- component knowledge accumulation. However, some specialization between architectural developers and components developers may take place as observed by Brusoni and Prencipe in the aircraft engine and chemical plant production. Their study do, however, reveal that developers of new product architectures typically had a wide technology base, a good understanding of customer needs and undertook some detailed design in particulary critical components. Moreover, they coordinated development work across firms through highly interactive types of information structures.

Other factors that may influence the link between product and organizational design stem from the trade-off between accumulation of the kind of knowledge that underlie functional expertise and the kind of knowledge accumulation that underlie product or component expertise. When both types of knowledge is necessary in to ensure effective innovativeness task definitions may have to encompass both "functional" and project activities. This may require more extended coordination of project due to capacity constraints and due to the gradual entrance and exit of project team members. Finally, the efficient organization of product development also needs to take incentive considerations into account.

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Table 1

The revenue and cost functions of different choices of concepts and technology

A	B	b_1 b_x	b_y	b_2 b_x	b_y
a_1	A_y	P0-co	p0-c1-f1-f2	p0-c0	p0-c1-f1
	A_x	2p1-2c0	2p1-2c1-f1-f2	2p1-2c0	2p1-2c1-f1
a_2	A_y	p0+r-c0	p0+r-c1-f1-f2	p0+r-c0	p0+r-c1-f1
	A_x	2p1+2r-2c0	2p1+2r-2c1-f1-f2	2p1+2r-2c0	2p1+2r-2c1-f1

Table 2

Optimal choice of concepts and technology when customer preferences are decisive

A	B	b_1 b_x	b_y	b_2 b_x	b_y
a_1	a_y	p0-co *	p0-c1-f1-f2	P0-c0	p0-c1-f1 *
	a_x	2p1-2c0	2p1-2c1-f1-f2	2p1-2c0	2p1-2c1-f1
a_2	a_y	p0+r-c0	p0+r-c1-f1-f2	P0+r-c0	p0+r-c1-f1
	a_x	2p1+2r-2c0	2p1+2r-2c1-f1-f2 *	2p1+2r-2c0	2p1+2r-2c1-f1*

Table 3

Optimal choice of concept and technological solution if there is no decisiveness in decisions.

A	B	b_1 b_x	b_y	b_2 b_x	b_y
a_1	a_y	p0-co *	p0-c1-f1-f2	P0-c0*	p0-c1-f1
	a_x	2p1-2c0	2p1-2c1-f1-f2	2p1-2c0	2p1-2c1-f1
a_2	a_y	p0+r-c0*	p0+r-c1-f1-f2	P0+r-c0	p0+r-c1-f1
	a_x	2p1+2r-2c0	2p1+2r-2c1-f1-f2	2p1+2r-2c0	2p1+2r-2c1-f1*