Cooperative cellular manufacturing system: a cooperative game theory approach
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Abstract. In the cellular industry, the components of products are increasingly being manufactured by multiple companies, which are distributed across different regions resulting in increased production costs. Here, a cooperative cellular manufacturing system is introduced to decrease these costs. A mathematical programming model has been proposed, which evaluates the production cost when companies work independently and the model is then extended to consider coalitional conditions in which the companies cooperate as an integrated cell formation system. A key question that arises in this scenario is how to arrange the cells and machines of multiple companies when their cell formation systems are designed cooperatively. Through a realistic case study of three high-tech suppliers of the Mega Motor Company, we show that these companies can reduce the costs through a cooperative cellular manufacturing system. We then compute the cost saving of each coalition of companies obtained from cooperation to get a fair allocation of the cost savings among the cooperating firms. Four cooperative game theory methods including Shapley value, τ-value, core-center, and least core are proposed to examine fair sharing of cost saving. A comprehensive analysis of the case study reveals important managerial insights.

Keywords: Cell formation problem; Cellular manufacturing system; multi plants; Cooperative game theory; cost saving

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1. Introduction

At present, a typical production process involves construction, manufacturing, and supply activities, which are distributed among different geographical locations [1]. Cooperative production processes between these activities are increasingly being preferred when the potential benefits are large. For instance, a change in the economic atmosphere and reduced sales of automotive Iranian companies have motivated the thought process on how the production cost can be decreased by reorganization of the dependent facilities that operate in the same region. Assume that a large automobile company manages several smaller companies that produce different parts by the cellular manufacturing system (CMS). If these companies cooperate in the production processes and share their free capacities, the costs involved may be reduced.

When companies decide to form coalitions, answers to the following two questions become crucial: (i) how can the machines be arranged in the cells in order to minimize the production costs; and (ii) how the cost saving should be allocated among the companies in a fair manner?

To give an idea of the research problem at hand, we illustrate the case study of the suppliers of the Mega Motor Company. This company produces engines, gearboxes, and axles for the main Iranian automotive enterprises. We studied the cooperation opportunity of three companies: Behran-Mehvar, Saipa-Piston, and Saipa-Polos that manufacture similar products by adopting the cellular manufacturing technology and operate in the region of Golpayegan industrial park, Isfahan. These companies cater to a considerable proportion (in total 87%) of the different piston demands of the Mega Motor Company. Another company, Saipa Azarbayejan, competes with these companies supplying 13% of the demands and is located in Tabriz, which is far from the three companies. Figure 1 illustrates the company locations on the map. Distance wise, Golpayegan is 380 km from Tehran while Tabriz is situated 680 km away from Tehran. Evidently, the cost and time of transportation is greater for Saipa Azarbayejan and therefore from Mega Motor’s point of view, getting supplies from Golpayegan is certainly economical. Further, Behran-Mehvar, Saipa-Piston, and Saipa-Polos have several CNC machines with free capacities. So if these companies cooperate and share the machine capacities, they can cover the supply contribution from Saipa Azarbayejan. Therefore, in CGT, two challenging questions need to be answered [2]:

1. How can the profit of participants be computed in a cooperative environment?
2. How should the extra profit obtained from the cooperation be fairly divided among the participants?
3. How to reduce of intra-cell material handling cost?
4. How to reduce of inter-cell material handling the cost?

![Locations of the companies](image)

**Fig. 1.** Locations of the companies

The rest of this paper is organized as follows. Section 2 reviews the related researches. Prerequisites and assumptions of the proposed models are defined in Section 3. The proposed models are described in the non-coalitional condition in Section 3.1 and in the coalitional condition in Section 3.2. Section 4 provides a real case study about the cooperation problem between suppliers of the Mega Motor Company and the methods of cost saving allocation supported on cooperative game theory (CGT). Section 5 derives the contributions of the paper and some suggestions for the future researches.

2. Literature review

This study is mainly concerned with two issues: blood supply chain and cooperative game theory. Therefore, a full review of the literature on these topics is provided in the following sections.
2.1. Survey on cellular manufacturing systems

Cellular manufacturing (CM) is a method for manufacturing process in which each manufacturing cell is composed of a group of machine tools. In a CMS, the machine tools used to process a family of parts are joined together and form a cell. CM has the flexibility of job shops in addition to the high production rate of flow lines [3]. Therefore, the goal of cellular manufacturing is to have the flexibility to manufacture a high diversity of products with medium demand, while keeping the high productivity of large scale production. The benefits of implementing a cellular production system have been mentioned in numerous articles, including reducing parts preparation time, reducing inventory during manufacturing, reducing cost and time of material displacement, and improving production planning [4,5].

Several studies have considered inter- and intra-cell material handling in static conditions. Dimopoulos and Zalzala [6] introduced a method for job assignment selection for each operation, the layout of the cells in the job shop, the layout of the machines within the cells, and design of the transportation system. Akturk and Turkcan [7] solved a mixed integer programming model and considered superseded layout, routing, cell size, low utilization, and low-profit level constraints. Their model has certain advantages in terms of production volumes, processing times, and operation sequences. Mahdavi and Mahadevan [8] presented an algorithm to specify the layout of the machines within each cell and machine groups and the part families simultaneously. Recent studies have concentrated on inter- and/or intra-cell material handling in a dynamic production environment (i.e., dynamic cellular manufacturing system (DCMS)). Defersha and Chen [9] established a mathematical programming model for cell configuration according to tooling requirements of the parts and the machines. Their model offers certain features such as dynamic cell configuration, alternative routings, machine capacity, operation and setup cost. Ahkioon et al. [10] focused on arranging CMSs by considering multi-period production planning, operation sequence, machine capacity, and machine procurement. Kia et al. [11] studied a multi-floor layout design and proposed a mixed-integer programming model for a dynamic environment. The idea of their model was to determine the cell formation (CF) as well as group layout (GL) in a multi-period planning horizon simultaneously. Kia et al. [12] also developed a mixed-integer non-linear programming model for DCMS in which the products and part demands may change during the planning horizon.
Tavakkoli Moghaddam et al. [13] established a new mathematical model to evaluate facility layout problem in CMS when the demands are stochastic. The minimization of inter- and intra-cell material handling costs was considered as objective function. Wang et al. [14] formulated a new mathematical model for CMS that considers the demand changes over the product life cycle. The objective function of the proposed model was to minimize inter- and intra- material handling costs. Wang and Sarker [15] suggested a quadratic assignment problem (QAP) for the layout of machine-cells to minimize the inter-cell material handling cost. Bagheri and Bashiri [16] presented a new mathematical programming model that provides a solution to the cell formation, operator assignment, and inter-cell layout problems, simultaneously. They considered minimizing the costs of inter- and intra-cell part handling, reallocation of the machines, relocation, and operators as the objective function. Chen and Cao [17] suggested an integrated model to determine times to begin part-processing decisions. Their model minimizes the sum of costs arising due to inter-cell material handling and manufacturing cell construction. Safaei et al. [18] considered a sequence of operations, alternative process plans and machine replication and presented a mixed-integer programming model by assuming a dynamic environment. The objective function of the model was to minimize the summation of the inter- and intra-cell material handling and reconfiguration costs in addition to the machine constant and variable costs. Similarly, for DCMS, Mahdavi et al. [19] developed an integer non-linear mathematical programming model that incorporates hiring and firing of workers, worker assignments, and the available time of workers. The objective function of the model minimizes the summation costs of inter-cell material handling and reconfiguration of the machines, hiring, firing, and salary issues as well as holding and backorder. An integrated mathematical model was introduced by Safaei and Tavakkoli-Moghaddam [20] that minimizes machine costs, inter/intra-cell movement, reconfiguration, partial subcontracting, and inventory carrying costs. Saidi-Mehrabad and Safaei [21] used a neural network approach to solve the problem of dynamic production cell formation with the goal of minimizing the cost of reinstallation, fixed cost, and machine change by considering multiple paths and replicating machines. Schaller [22] proposed a linear integer model for the cell formation problem with the aim of minimizing the cost of producing parts, the constant cost of the machine, and the cost of moving the machine, and solved it using an extended banned search algorithm. In Table 1, we examine some of the research more closely.

**Table 1.** The publications related to the cellular manufacturing systems.
However, in all of these studies, it has been attempted to design cellular production systems to minimize intercellular displacements and optimal alignment. This makes it only part of the optimization of the system, which reduces the cost and time of operation and increases productivity. The research will show that the ability to collaborate with several manufacturing companies at the same time considering the conditions of the alliance can reduce the total cost, organize the cells and machines of different companies and achieve better solutions. The reviewed studies presented different models for CMS; however, none of them considered designing CMS for multiple cooperating companies. The cell formation problem for one company, discussed in the present paper, is somewhat similar to that of Kia et al. [11], wherein the intra- and inter-cell material handling costs and the determined demands are similar in both models. By employing the CGT concept, we add another dimension to the model by considering multiple independent companies that may form coalitions in a dynamic environment in order to reduce their production costs.

2.2. Survey on CGT and its applications

Game theory is categorized into cooperative game theory (CGT) and non-cooperative game theory (NCGT). In CGT, players are able to cooperate to create value by forming coalitions; however, they do not compete to obtain further value [21]. In some circumstances, by making binding agreements, the players cooperate with each other and organize the coalition. In the real world, the most obvious and common agreements between companies are formal legal contracts. In CGT, there are some players who form a coalition together. There is also a function called the characteristic function that denotes the game value of each coalition. The characteristic function incorporates an input to the solution concept, which returns the value captured by each player (their imputation).

Previous researchers have used the CGT to analyze problems such as routing and scheduling, forest transportation planning, logistics network, process planning, and production problems. Frisk et al. [23] investigated a forest transportation planning problem and evaluated various CGT methods for distributing the cost saving among the cooperating companies. Lozano et al. [24] established a linear transportation model and used it to determine the cost savings when different companies merge their transportation requirements. Using CGT approach, they calculated the cost saving achievable by the companies. Hafezalkotob and Makui [25] presented a robust optimization model for the multiple-owner logistic network problem and answered the question on how independent owners of a network should cooperate to obtain a reliable maximum flow. Mohebbi and Li [26] evaluated costs, shadow prices, and volume weights to distribute the total cost or
savings among the members. By adopting CGT methods such as the Shapley value, τ-value, and Maximin core, Zibaei et al. [27] evaluated the cost saving opportunity of cooperation in multi-depot vehicle routing problem.

Sakawa et al. [28] formulated a mathematical programming model to minimize the production and transportation cost in a cooperative environment. They assumed that the companies make multi products in different regions. They considered two important items: capacities of companies and demand in regions. They used this model in a housing material manufacturing case study and applied the CGT to obtain fair cost allocation. Curiel et al. [29] considered cost allocation problem under one machine-scheduling problem. Mohammaditabar et al. [30] concentrated on capacitated-supplier selection in a supply chain by considering inventory related costs. They proposed different CGT methods such as the Shapley value, τ-value, and least core for profit allocation among the members of a supply chain. Some other investigations are reviewed in Table 2.

Table 2. The review table of the game theory in Research dimensions.

2.3. Research gap and Contributions

Although cooperative production is a favorable strategy in the real world to reduce production costs and increase profit, there are few studies that have mathematically formulated cooperative production strategy. Previous researchers have proposed different models for the problem of cellular manufacturing, but to the best of the authors’ knowledge, there is no study that considered how the cellular manufacturing problem should be modeled when multiple companies with the cellular manufacturing technology decide to cooperate together. We call this system Cooperative Cellular Manufacturing System (Co-CMS). In Co-CMS, the agreements between companies depend on the costs that will be saved when they cooperate and also the contribution of each firm to the total cost saving. Therefore, an analytical method for estimating the cost savings and cost saving allocation should be adopted in Co-CMS, which is the main contribution of this study.

3. Methodology

Whenever a person (government or group, etc.) wants to do something in the face of others, his or her action may provoke the other party to these interactions when both parties are aware of their effects. Applies. Now players may agree on a strategy to choose from while playing the game. If the agreement between the players is enforceable and practicable, they call the game "cooperative" and if the agreement between the players is not enforceable and
practical, they call it "non-cooperative". In other words, if players can act on agreed principles, they will call the game cooperative.

In cooperative models, it is assumed that all players work together to achieve optimal results for the system. Thus in collaborative models, the problem is transformed from multi-decision and multi-criteria to single-decision and multi-criteria. Such a similarity, according to game theory experts, has led researchers to better understand and understand these models than non-cooperative models. Unlike cooperative game theory, which analyzes the actions and reimbursement of individual players, cooperative game theory examines the joint actions and collective reimbursement of a group of players (or coalitions). In reviewing the literature of transportation, one important question that cooperative game theory is concerned with is how to allocate costs or benefits among players in a fairway. Therefore, this system is stable and does not give players an incentive to leave the coalition [31]. Accordingly, in the proposed model of this research, decision-makers’ objective functions are merged and a hybrid goal function is created to transform the problem from multi-objective to single-objective.

The models for the non-cooperative and cooperative conditions (i.e., models (1)–(10) and (11)–(21), respectively) should be solved first for the companies. The optimal value of the objective function may represent the characteristic function of CGT which is the total production cost of company (or cooperating companies). The cooperation would be advantageous for the companies if they can obtain reasonable cost-saving from co-production. When the cooperation is reasonable, the cost-saving can be fairly distributed by some solution methods of CGT such as the Shapley value, core center, τ-value, least core, and equal cost saving method (ECSM) methods. Figure 2 illustrates the methodology of the Co-CMS.

**Fig. 2. Overview of the Co-CMS based on the CGT**

### 3.1. Mathematical models

In this section, a nonlinear mixed-integer programming model for the Co-CMS problem is presented with the aim of minimizing the total costs of inter- and intra-cell material handling and intra-factory material handling. The idea is to develop the model first by considering objective costs of the cell formation by each company independently and then for a coalition of the companies with CMS technology, i.e., Co-CMS. The Co-CMS is acceptable for cooperating companies if the optimal objective function in the cooperative scenario is lower than the sum of the individual minimum objective function costs (inter and intra-cell material handling, intra-company material handling and the benefits from
increased production) for the members of that coalition. Afterward, the model results are explained by evaluating the Co-CMS in a real cooperative environment for the suppliers of the Mega Motor Company.

3.1.1. Mathematical model in the non-coalition condition

In this section, we develop a mathematical model for CMS to determine the objective costs and cell arrangements when companies work independently. As mentioned, the first step is to solve this model for each company independently and then develop a model for all coalitions between two companies in the next section. Then, the model is solved for all coalitions between three companies, and so on, until a grand coalition is achieved. We make the following assumptions to establish the CMS model for multiple companies in non-coalition conditions:

**Assumption 1.** All operations of the products of a company should be processed in the factory of that company. Moreover, the products demand of a company should be satisfied by the production of that company.

**Assumption 2.** The companies produce similar products. Moreover, the production process of the products is assumed to be the same in each company. The companies may not use the same machines, but the machines are multi-functional which means that each operation of a product can be conducted on various machines with various processing times. This feature is called alternative process routings and causes flexibility in the process plan of the products [11].

**Assumption 3.** The CMS problem of multiple companies is considered in deterministic condition. Thus, the number of companies and locations are known in advance. The product demand for each company is identified in advance. The capacity of all machines and processing time of each product are predetermined. Moreover, the processing cost of each operation of a product is identified in advance.

**Assumption 4.** The cells in the plants are not physically separated. Indeed, the cell configuration is determined through the layout of a plant and it influences the material handling routes of semi-finished products.

**Assumption 5.** The inter- and intra-cell handling costs are different. That is, the inter- and intra-cell handling costs of semi-finished products are contingent upon the distance travelled. Therefore, the location of machine in cells and the location of cells in plant influence the handling costs of products.
Assumption 6. The maximum and minimum values exist for the cell sizes which are known in advance. It means there exist lower and upper bounds for all types of machines that can be located on the shop floor. However, the shape of cells is determined by the model in order to bear minimum inter- and intra-cell handling cost.

The indexes, parameters, and variables of the model can be expressed as follows:

- $P$ Index set of products;
- $M$ Index set of machines;
- $L$ Index set of location;
- $C$ Index set of cells;
- $k_p$ Index set of operation indices for product $p$;
- $t_{c_m}$ Available time capacity for machine $m$;
- $d_p$ Demand for product $p$;
- $t_{kpm}$ Processing time of operation $k$ on machine $m$ for each product $p$;
- $a_{kpm}$ 1 if the operation $k$ of product $p$ can be processed on machine $m$, otherwise, 0;
- $d_{i'l''}$ The distance between two locations $l$ and $l''$;
- $IE$ Inter-cell material handling cost for product $p$ per unit of distance;
- $IA$ Intra-cell material handling cost for product $p$ per unit of distance;
- $x_{kpm}$ The number of product $p$ processed by operation $k$ on machine $m$;
- $w_{mlc}$ 1 if machine $m$ is located at location $l$ and assigned to cell $c$, otherwise, 0;
- $y_{kpm}$ The number of product $p$ processed by operation $k$ on machine $m$ and moved to machine $m'$.

The following model is used to obtain the objective costs of each company when the companies work independently. This formulation is based on Kia et al. [11] and is given as:

$$
\text{Min } z = \sum_{c} \sum_{m} \sum_{l} \sum_{m',m''} \sum_{l',l''} \sum_{p} \sum_{k} w_{mlc} w_{m'l''} y_{kpm} d_{i'l''} E
$$

$$
+ \sum_{c} \sum_{c'} \sum_{m} \sum_{l} \sum_{m',m''} \sum_{l',l''} \sum_{p} \sum_{k} w_{mlc} w_{m'l''} y_{kpm} d_{i'l''} IA,
$$

subject to

$$
x_{kpm} \leq a_{kpm} M , \quad \forall k \forall p \forall m ,
$$

$$
\sum_{m} x_{k=1,pm} \geq d_p , \quad \forall p \forall k ,
$$

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Objective function (1) comprises two parts: the first part indicates intra-cell material handling cost while the second part indicates inter-cell material handling the cost. Constraint set (2) ensures that each operation of a part is performed on the machine that is able to perform that operation. The demand satisfaction condition for all parts is guaranteed by Constraint set (3). Constraint (4) states that the total number of machines of all types utilized in the shop floor should not be greater than value $L$. Constraint (5) states that at least one machine of all types should be used on the shop floor. Constraint set (6) is the capacity limitation constraint of each machine and expresses that when machine type $m$ is used, the total processing time of this machine should not be greater than its time capacity. Material flow conservation conditions are ensured by Constraint sets (7) and (8). Constraint set (9) is to guarantee that each location can be simultaneously occupied at most by one machine. Constraint set (10) means that each machine should only belong to one location of a cell.

3.1.2. Mathematical model in the coalitional condition

In Co-CMS, the cooperating companies should identify the arrangement of machines in the cells and the production process of products to evaluate the production cost of the entire system. We now develop a mathematical model to calculate the optimal cost of Co-CMS. First, prerequisites and assumptions are defined as follows:
Assumptions 2–7 of CMS in the non-coalition environment are also considered in Co-CMS. Moreover, the following assumptions are introduced to establish the framework of the Co-CMS model:

**Assumption 1.** The operations of a company product can be processed in the factory of cooperating companies. Moreover, the demand products of a company can be satisfied by the production of other cooperating companies.

**Assumption 2.** When semi-finished products are transferred between factories of cooperating companies, the intra-factory material handling cost is incurred by the coalition. The intra-factory material handling cost depends on the distance traveled. Therefore, the location of factories directly affects the total cost of the Co-CMS. The handling costs among cooperating factories should not be too high relative to cellular manufacturing costs. Otherwise, the high handling costs among factories diminish synergy of cooperation and the players may withdraw from the Co-CMS.

**Index**

- **P** Index set of the products;
- **F** Index set of the factories;
- **M<sub>f</sub>** Index set of the machine indices for factory <i>f</i>;
- **k<sub>p</sub>** Index set of the operation indices for product <i>p</i>;
- **c<sub>f</sub>** Index set of the cell indices for factory <i>f</i>;
- **l<sub>f</sub>** Index set of the location indices for factory <i>f</i>.

**Model Parameters**

- **t<sub>cm</sub>** Available capacity for machine <i>m</i>;
- **d<sub>pf</sub>** Demand for product <i>p</i> in factory <i>f</i>;
- **d<sub>dpf</sub>** Demand for product <i>p</i> in factory <i>f</i>, if the factories cooperate together;
- **t<sub>kpm</sub>** Processing time of operation <i>k</i> on machine <i>m</i> for each product <i>p</i>;
- **a<sub>kpm</sub>** 1 if operation <i>k</i> of product <i>p</i> can be processed on machine <i>m</i>, otherwise, 0;
- **p<sub>vmf</sub>** 1 if machine <i>m</i> belongs to factory <i>f</i>, otherwise, 0;
- **p<sub>lf</sub>** 1 if location <i>l</i> belongs to factory <i>f</i>, otherwise, 0;
The distance between two locations $l$ and $l'$;

$IE$  Inter-cell material handling costs for product $p$ per unit of distance;

$IA$  Intra-cell material handling costs for product $p$ per unit of distance;

$IT$  Intra-factory material handling costs for product $p$ per unit of distance;

$sav_p$  Profit from selling of product $p$.

**Variables**

$w_{mlc}$  1 if machine $m$ is located at location $l$ and assigned to cell $c$, otherwise, 0;

$y_{kpm}$,  The number of product $p$ processed by operation $k$ on machine $m$ and moved to machine $m'$;

$x_{kpm}$  The number of product $p$ processed by operation $k$ on machine $m$.

In a coalitional condition, the companies with excess capacities can cooperate together by sharing these capacities. When two or more companies cooperate together, the intra-factory costs should be added to the basic model. On the other hand, the companies can reduce their overload costs by increasing the rate of production. Therefore, the benefit from increased production is added to the objective function. This factor has a reverse effect on the total costs. The final model is hence given as:

$$
\text{Min } z = \sum_{f \in F} \sum_{c \in C} \sum_{m \in M_f} \sum_{l \in L_f} \sum_{m' \in M_f} \sum_{l' \in L_f} \sum_{l \neq l'} \sum_{p \in P} \sum_{k \in K} w_{mlc} w_{ml'l'} y_{kpm'} dic_{ll'} \cdot IE \\
+ \sum_{f \in F} \sum_{c \in C} \sum_{m \in M_f} \sum_{l \in L_f} \sum_{m' \in M_f} \sum_{l' \in L_f} \sum_{l \neq l'} \sum_{p \in P} \sum_{k \in K} w_{mlc} w_{ml'l'} y_{kpm'} dic_{ll'} \cdot IA \\
+ \sum_{f \in F} \sum_{c \in C} \sum_{m \in M_f} \sum_{l \in L_f} \sum_{m' \in M_f} \sum_{l' \in L_f} \sum_{l \neq l'} \sum_{p \in P} \sum_{k \in K} w_{mlc} w_{ml'l'} y_{kpm'} dic_{ll'} \cdot IT \\
+ \sum_{p \in P} \sum_{f \in F} (d_{pf} - d_{1pf}) sav_p,
$$

subject to

$$
x_{kpm} \leq a_{kpm} M, \quad \forall k \quad \forall p \quad \forall m, 
$$

$$
\sum_{m} x_{k,l,m} \geq \sum_{f} d_{pf}, \quad \forall p \quad \forall k, 
$$

$$
\sum_{m \in M_f} \sum_{l \in L_f} \sum_{c \in C_f} w_{mlc} \leq l_f, \quad \forall f, 
$$

\(-13\)
\[
\sum_{m \in m_f} \sum_{l \in l_f} \sum_{c \in c_f} w_{mlc} \geq 1, \quad \forall f,
\]
\[
\sum_{p} \sum_{k} x_{kpm} t_{kpm} \leq tc_m, \quad \forall m,
\]
\[
x_{kpm} = \sum_{m} y_{kpmm'}, \quad \forall k \quad \forall p \quad \forall m,
\]
\[
x_{kpm'} = \sum_{m} y_{k-lpm'm'}, \quad \forall k \quad \forall p \quad \forall m',
\]
\[
\sum_{c \in c_f} \sum_{m \in m_f} w_{mlc} \leq 1, \quad \forall l,
\]
\[
\sum_{l} \sum_{c} w_{mlc} = 1, \quad \forall m,
\]
\[
w_{mlc} \leq pv_{my} p_{if}, \quad \forall f \quad \forall c \in f \quad \forall m \quad \forall l.
\]

Objective function (11) minimizes the sum of inter- and intra-cell material handling costs, as well as the intra-factory material handling cost with considering the benefits achievable from increased production in order to reduce the manufacturing overload costs. Constraint set (12) ensures that each operation of a product is processed on the machine that is able to process that operation. The demand satisfaction conditions for all the products are guaranteed by Constraint set (13). Inequalities (14) and (15) necessitate that the number of machines used on the shop floor is lower than the number of existing locations on the shop floor and that it is greater than 1. Inequalities (16) are machine capacity constraints, while Constraint sets (17) and (18) preserve the material flow conservation equations. Constraint sets (19) and (20) certify that at a same time, each location can gain one machine at most and only belongs to one cell. Constraint set (21) guarantees that a machine is allowed to be placed at a location if and only if the machine and location both belong to the same factory.

To linearize model (11)–(21), we employ a procedure used by Kia et al. [11] and hence apply the below-mentioned changes. The non-negative variables \( yy_{kpmmf'c} \) and \( yy_{kpmmf'c'} \) are introduced by the following equations:

\[
w_{mlc} w_{mlc'f} y_{pmm'} = yy_{kpmmf'c}, \quad (22)
\]
\[
w_{mlc} w_{mlc'f} y_{pmm'} = yy_{kpmmf'c'}. \quad (23)
\]

Thus, the following constraints are added to the basic model:
The linearization helps in solving the model by linear programming package. Now, the first model should be solved to achieve the objective cost for the companies when they work independently and then evaluate the objective function for all possible coalitions. At the end, the share of each company in cost saving is determined by methods such as the Shapley value and core center.

The model is developed by adding the intra factory costs to the objective function. Each company determines its capacity of sale and production. When companies cooperate, they can increase their production capacity but not more than the sale capacity. Therefore, the maximum range of production is sale capacity. Moreover, according to the concept of economy of scale, an increase in the production volume can decrease the final overhead costs and cost of production. Thus, the difference between the quantity of production before and after the cooperation results in lower production cost. This factor will, therefore, be considered as the objective function.

3.2. Cooperative game theory approach

We now evaluate the problem of how to distribute the cost-saving due to the cooperation among different companies. This problem exists in several real world situations where the independent companies are capable of co-operating in order to reduce the cost of their activities. This problem should be addressed with regard to the contribution of each company in different possible coalitions. CGT is an appropriate approach to tackle this problem and provides a general framework to evaluate the cost-savings allocation problems [24, 25]. By evaluating all possible coalitions of the cooperating companies, CGT provides a set of methods for distributing the obtained cost-savings in a fair manner. Some basic concepts and methods related to CGT are briefly reviewed as follows (for details see [23, 24, 25, 32]).

In CGT, the players have an incentive to cooperate if their cooperation leads to sufficient synergy. According to the supper additive property of CGT, the optimal cost function for any coalitional situation should be lower than the total individual optimum cost function of the coalition members [24]. In Co-CMS, it means that the cost-savings of Co-CMS should justify the cooperation. This point is mathematically expressed as:

\[ y_{kpmnlc} \geq y_{kpmnlc} - M \left( 2 - w_{mle} - w_{m'l'c'} \right) \quad \forall k \forall p \forall m,m' \neq m \forall l,l' \neq l \forall c \forall c' \forall f, \quad (24) \]

\[ y_{kpmnlc} \geq y_{kpmnlc} - M \left( 2 - w_{mle} - w_{m'l'c'} \right) \quad \forall k \forall p \forall m,m' \neq m \forall l,l' \neq l \forall c,c' \neq c \forall f. \quad (25) \]
\[ TC(S) \leq \sum_{j \in S} TC(j). \]  

The difference between the minimum cost of coalition \( S \) and the summation of individual minimum costs reflects the cost-savings of that coalition [24], \( CS(S) \), that is
\[ CS(S) = \sum_{j \in S} TC(\{j\}) - TC(S). \quad (27) \]

The cost-saving should be estimated considering the cost of the cooperating companies. Consequently, similar to [24, 25] we define synergy of a coalition as:

\[ Synergy(S) = \frac{CS(S)}{TC(S)}. \quad (28) \]

Several methods have been proposed in CGT; however, we focus on the Shapley value, least core [33], \( \tau \)-value [34], core center [35], and ECSM [21, 27, 25] in this study.

Shapley [36] developed a CGT method for distributing payoff of cooperation based on expected marginal contribution of each player in different coalitions. Four axioms of efficiency, symmetry, additive, and dummy property are considered in Shapley method [37]. In Co-CMS, based on the cost-saving of coalitions, the Shapley value determines cost-saving of each cooperating company as follows:

\[ y_j = \sum_{S \in N, j \in S} \frac{(|S|-1)!-(|N|-|S|)!}{|N|!} [CS(S) - CS(S - j)]. \quad (29) \]

Here \(|S|\) denotes the number of participants in coalition \(S\). The value of \(CS(S) - CS(S - j)\) represents the amount by which the cost of coalition \(S - j\) increases when participant \(j\) joins it. The Shapley value assigns the cost-saving to each company by calculating the sum of the marginal contribution of that company over all possible coalitions.

The core embraces an important concept in CGT and represents the set of feasible assignments that cannot be enhanced by any coalition of the players. The core of a cooperative game can be denoted by

\[ \text{core}(0) = \{ \bar{y} \in Y | e(S, \bar{y}) \leq 0, \forall S \subset P \} = \{ \bar{y} \in Y | CS(S) \leq \sum_{j \in S} y_j, \forall S \subset P \}. \quad (30) \]

The game is stable if and only if the core is non-empty. Moreover, for real number \(\varepsilon\), \(\varepsilon\)-core is as follows

\[ \text{core}(\varepsilon) = \{ \bar{y} \in Y | e(S, \bar{y}) \leq \varepsilon, \forall S \subset P, S \neq P, S \neq \emptyset \}. \quad (31) \]
The first $\varepsilon$ value for which $\text{core}(\varepsilon) \neq \emptyset$ is named the least core. The least core (or the minimax core) can also be obtained from the following linear programming problem

Min $\varepsilon$,
subject to
$$e(S, \bar{y}) = \nu(S) - \sum_{j \in S} y_j \leq \varepsilon, \text{ for all } S \subset P, S \neq P.$$  \hspace{1cm} (32)

ECSM is a novel allocation method based on equal profit method developed by Frisk et al. [23]. ECSM provides similar relative cost-saving for manufacturing companies. It minimizes the maximum difference in pairwise cost-saving of the companies. The linear programming problem of ECSM is formulated as follows:

Min $\lambda$,
subject to
$$\lambda \geq |z_i - z_j|, \forall (i, j) \in K,$$
$$\sum_{i \in S} z_i \geq CS(S), \text{ for all } S \subset K, S \neq P,$$
$$\sum_{i \in P} z_i = CS(P).$$  \hspace{1cm} (33)

The first constraint states that the variable $\lambda$ is the largest difference between cost-saving assignments and should be minimized in the objective function. The second and third constraints ensure that the solution of ESCM should belong to core space so that it could give a stable solution.

In CGT, $\tau$-value is an important method that is composed of the upper vector $M(K,CS)$ and lower vector $m(K,CS)$. $M_k$ is the $k$th coordinate of $M(K,CS)$ and represents the maximum right value for player $k$ from the grand coalition. Furthermore, $m_k$ is the $k$th coordinate of $m(K,CS)$ and represents the minimum right value for player $k$ from grand coalition. For the cost-saving value of cooperating companies, $M_k$ and $m_k$ are formulated as:

$$M_k = \text{CS}(K) - \text{CS}(K \setminus \{k\}),$$

$$m_k = \max_{S_m \in S_m} \left\{ \text{CS}(S_m) - \sum_{k \in S_m \setminus \{k\}} M_k \right\}.$$  \hspace{1cm} (34)
In Co-CMS, $M_k$ and $m_k$ represent the maximum and minimum rights of cost-saving allocation for company $k$. The $\tau$-value method computes an imputation based on $M(K,CS)$ and $m(K,CS)$ as follows:

$$\tau_k = m_k + \alpha(M_k - m_k),$$

(36)

in which $\alpha \in [0,1]$ can be uniquely evaluated through $\sum_{k \in K} \tau_k = CS(K)$.

In the next section, we employ these methods of CGT in the case study of Co-CMS for the Mega Motor Company.

4. Case study

The Mega Motor Company sees its mission in improving general property and sustainable development through designing and manufacturing power train for the automotive industry by means of advanced technology. Mega Motor gets the supplies of pistons for internal combustion engines from four main companies: Behran-Mehvar, Saipa-Piston, Saipa-Polos, and Saipa Azarbanyejan. Mega Motor provides these suppliers with raw materials (i.e., alloy ingots named LM13) at a certain rate and purchases products thereafter. Thus, each supplier company has a specific contribution to supply Mega Motor’s demand of pistons. A piston is a significant component of internal combustion engines that transforms energy obtained from the fuel combustion in a cylinder into beneficial mechanical power. Manufacturing process of piston includes five steps: casting, heat treatment, machining process, pin fitting, and inspection. The machining process contains three steps: drilling, grinding, and reaming. The four suppliers perform these steps by different high-tech CNC machines. The suppliers try to increase their benefit by controlling their overload costs, especially the transformation costs. If the companies can meet greater portion of the product demand, they may be able to reduce their overload costs.

We evaluate Co-CMS of three suppliers, i.e., Behran-Mehvar, Saipa-Piston, and Saipa-Polos, that operate in Golpayegan industrial park (see Fig. 1). These suppliers are called f1, f2, and f3. Figure 3 shows how these companies with the CMS framework can cooperate. It can be understood from Fig. 3 that when the companies form a coalition, three types of transportation costs are incurred including inter- and intra-cell material handling costs and intra-factory transfer cost.

**Fig. 3.** The three factories with cell formation framework in cooperation with each other.
The data such as the distances between locations, machines capacities, characteristics of machines performance and financial data are real. The detailed data for the grand coalition are indicated in Table 3. A numerical example of the mathematical programming model has been solved in all possible coalitions of the three companies. Table 4 lists important decision variables of each coalition (\{f1, f2\}, \{f1, f3\}, \{f2, f3\}, and \{f1, f2, f3\}). Moreover, Fig. 4 illustrates the cell formation structure of Co-CMS in the grand coalition of the three factories.

**Table 3.** Parameters of the numerical example (the detailed data of the grand coalition of the factories)

**Table 4.** Two important variables of numerical example, \(y\) number of the products transferred between the machines, \(w\) machine allocation in the cells

**Fig. 4.** Transportation between different factories in Co-CMS

We use the case study to explain the performance of the CGT methods in fair allocation of cost-saving of Co-CMS. At the first step, the CSM model (1)--(10) should be solved for \{f1\},\{f2\} and \{f3\} and then Co-CSM model should be solved for each possible coalition \(S\), i.e., \{f1, f2\}, \{f1, f3\}, \{f2, f3\}, and \{f1, f2, f3\}. Table 5 illustrates the minimum total cost \(TC(S)\) obtained from the optimum objective function of the models. Moreover, Table 5 shows the cost-saving and synergy of each coalition computed by Eqs (27) and (28), respectively. The cost-saving is zero if a company works independently and the cost-savings and the synergies grow as the coalition size increases.

**Table 5.** Total cost, cost-saving, and synergy of all possible collations

Using the characteristic functions of cost saving (CSs) from Table 5, we compute the cost-saving assignment methods based on the Shapley value, \(\tau\)-value, cores center, least core, and ECSM as discussed in Section 3. The results of the methods are summarized in Table 6. We use Lingo 11 package to obtain the optimum solution for the least core problem (32) and ECSM problem (33). Other assignments of Table 6 are achieved based on TUGlab platform [35].

In this study, we first used the cooperative game theory to solve the problem of cellular production. Given the small dimensions of the problem in the case study investigated in the research and the use of real-world data extracted, the optimal solution was obtained. In other words, the exact method of solving and modeling with Lingo helped us to achieve the optimal solution in the shortest time.
Table 6. Cost-saving assignment of Co-CMS based on CGT methods.

The satisfaction of coalition $S$ is obtained as the difference between the allocated cost-saving of each coalition and the total share of each company from the achieved cost-savings, i.e.,

$$F_s (CS, y) = \sum_{p \in S} y_p - CS (S) \quad \forall S \neq \emptyset, S \subseteq N.$$  \hfill (37)

Table 7 shows the satisfaction values, $F_s (CS, y)$, for coalition $S$ obtained from the aforementioned CGT methods and relative satisfaction with respect to coalition cost $TC (S)$ which is computed as $100 \times F_s (CS, y)/TC (S)$. The obtained results reveal that satisfaction of the coalitions decreases as the coalition size grows. The minimum satisfaction among the coalitions for each solution has been shown in the last row of Table 7. The results show that the Shapley value, τ-value, core center, and least core methods have the largest minimum relative satisfaction (20%). The least satisfaction can be interpreted as a measure of the core centeredness of each solution and states the minimum distance of the solution from the facets of the core boundary [24]. It is also a simple measure of the degree of stability of each solution. Table 7 also shows that the maximum least satisfaction in terms of $F_s (CS, y)$ corresponds to the least core method.

Table 7. Coalition satisfactions in Co-CMS for different CGT methods

The mean absolute deviation (MAD) was utilized to measure the similarity between the five tested cost-savings allocation methods. The MAD is computed from the following formula:

$$MAD (\bar{y}, \bar{y}') = \frac{|N|}{CS (N)} \sum_p (\bar{y} - \bar{y}').$$ \hfill (38)

In Co-CMS, the MAD of the cost saving shares allocated to the different companies is presented in Table 8. From the MAD, we find that the Shapley, τ-value and core center methods give similar solutions for the cost-saving allocation problem.

Table 8. The values of MAD

Now, we graphically evaluate the imputation and core sets and show the solutions of the Shapley value, τ-value, core-center, mini max core, and ECSM methods. For the Co-CMS of the three suppliers, Fig. 5 depicts the core and imputation sets. All CGT solutions
are also illustrated in Fig. 5. All solutions are stable imputations because they are located in the core set. From Fig. 5, we also find that the Shapley value, τ –value and core-center methods present very close cost-saving assignments.

**Fig. 5.** Core solution (CS) of three different factories

**Fig. 6.** Sensitivity analysis of the Shapley values with respect to the changes in intra-factory transportation cost (with coefficient λ)

Figure 6 represents the sensitivity analysis of the Shapley value assignment in Co-CMS with respect to the intra-factory transportation cost of the first company (with the coefficient λ). The results show that the cost-saving assignment to the first company decreases as its transportation cost increases whereas the cost-saving assignments of the other companies remain almost unchanged. Furthermore, the figure shows that the cost-saving of the grand coalition also decreases. When the intra-factory cost increases, reduction of the total cost-saving leads to changing of the core set according to Fig. 7. This figure shows four core sets for different λ-values (λ = 1, 1.4, 1.8, and 2). From the figure, we find that the core set of the Co-CMS shrinks as the intra-factory transportation costs increase. The Shapely values are also demonstrated in each core set [24].

**Fig. 7.** The changes in core set with respect to the increases in intra-factory cost (with coefficient λ)

In Table 9, the revenue, cost, and profit of each possible coalition are reported when the companies supply different percentages of the Mega Motor’s demand. The companies can improve their profit by controlling their production cost through cooperation. From the Figure. 8, we know that when the companies completely use their capacity, they can decrease their overload costs. If the three companies cooperate for sharing their excess capacities and supply a larger portion of the Mega Motor’s demand, then they can gain greater earnings.

**Fig. 8.** Changing of profit and cost for each possible coalition by supplying different percentages of demand

**Table 9.** Detailed data of revenue, cost, and profit for each coalition

The numerical example gives us the following managerial insights:

- In the Co-CMS, the semi-finished products can be freely transported among the cooperating companies. Therefore, the Co-CMS may give a completely different
solution relative to multi-site CMS with no-cooperation. The intra-factory transportation cost is a key factor for effective cooperation in Co-CMS.

- In Co-CMS, the cooperating companies may share the capacities of machines and reduce the production cost. Thus, the cooperation between the companies can improve their competitive advantage. For example, three suppliers of Mega Motor can effectively supply a large proportion of its demand through cooperation.
- When the intra-factory cost of a cooperating company in Co-CMS increases, it negatively affects the cost of the whole system. Moreover, the company will gain lower share from the total cost-saving due to its low effectiveness.
- Various cost-saving methods yield different assignments; however, the Shapley, $\tau$-value, and Core center methods give similar solutions in the presented case study. The best method should be selected based on the satisfaction of cooperating companies, because a fair assignment of cost-savings encourages the companies to continue their cooperation in Co-CMS.

5. Conclusion and further research

This research established a mathematical programming model for Co-CMS to formulate cooperative manufacturing problem. By applying the coalition concept of CGT, we show that when cooperating companies with CMS technology form a coalition, they can reduce the cost by sharing the capacities. Indeed, synergy derived from the cooperation offers some incentives for the companies to organize large coalitions. Successful implementation of Co-CMS depends on a fair assignment of cost-savings of collaboration, which motivates the companies to continue their cooperation. Thus, we proposed a set of solution methods including the Shapley value, $\tau$-value, least core, and core center to distribute cost-savings of Co-CMS among cooperating companies in a fair manner. To obtain an insight into the problem and examine the behavior of the proposed solution methods, a real case study of the Mega Motor Company was thoroughly evaluated in which its three suppliers: Saipa-Piston, Behran-Mehvar and Saipa-Polos with CMS technology planned to work together.

There are several issues for further research. In the model proposed in this study, some assumptions are considered, for example, the companies manufacture similar products with the same operation. Eliminating these assumptions and adding the workers' limitation to the proposed model would also be interesting. Moreover, considering virtual cells is significantly important. In this paper, it has been assumed that all the players are ready to
share the whole extra capacities. However, there may be companies that wish to share just a part of their extra capacity and studying Co-CMS in this situation would be very interesting. Moreover, analyzing the Co-CMS in an uncertain environment can be further studied in the future researches.

References


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Figure 1.
Develop a mixed-integer nonlinear programming model for two environments:
the non-coalitional and coalitional conditions

Solve the models to estimate the characteristic function for each possible coalition

Calculate the cost saving achieved by each coalition

Is the cooperation advantageous?

Companies prefer to work independently

Calculate the benefits of cost saving for each company by using the Shapley value, core center, τ-value, least core, and ECSM methods

Analyze the stability of solutions by using imputation and core concepts

Figure 2.

Figure 3.
Figure 4.

Figure 5.
Figure 6.

Figure 7.
Figure 8.
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<td>lo1</td>
<td>lo2</td>
<td>lo3</td>
<td>lo4</td>
</tr>
<tr>
<td>lo1</td>
<td>0</td>
<td>10</td>
<td>1800</td>
</tr>
<tr>
<td>lo2</td>
<td>10</td>
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<td>1200</td>
</tr>
<tr>
<td>lo3</td>
<td>1800</td>
<td>1200</td>
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</tr>
<tr>
<td>lo4</td>
<td>1500</td>
<td>850</td>
<td>7</td>
</tr>
<tr>
<td>lo5</td>
<td>1350</td>
<td>1000</td>
<td>11</td>
</tr>
<tr>
<td>lo6</td>
<td>2000</td>
<td>1700</td>
<td>3000</td>
</tr>
<tr>
<td>lo7</td>
<td>2020</td>
<td>1500</td>
<td>2800</td>
</tr>
<tr>
<td>lo8</td>
<td>1800</td>
<td>1680</td>
<td>2500</td>
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</table>

<table>
<thead>
<tr>
<th>d1(p,f)</th>
<th>d(p,f)</th>
<th>cell(c,f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pin</td>
<td>pinu4</td>
<td>pin</td>
</tr>
<tr>
<td>f1</td>
<td>6500</td>
<td>6000</td>
</tr>
<tr>
<td>f2</td>
<td>8000</td>
<td>9000</td>
</tr>
<tr>
<td>f3</td>
<td>8000</td>
<td>8500</td>
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IA=500  IE=500  IT=30  pro(pin)= 80000  pro(pinu)= 50000
Table 4.

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<thead>
<tr>
<th>Coalition{f1, f2}</th>
<th>y(k,p,m,m')</th>
<th>w(m,l,c)</th>
<th>y(k,p,m,m')</th>
<th>w(m,l,c)</th>
<th>y(k,p,m,m')</th>
<th>w(m,l,c)</th>
<th>y(k,p,m,m')</th>
<th>w(m,l,c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalition{f1, f3}</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Coalition{f1, f2, f3}</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>k1pin m2m1</td>
<td>1,457</td>
<td>m1lo2c1</td>
<td>1</td>
<td>k1pin m2m1</td>
<td>11,666</td>
<td>m1lo1c1</td>
<td>1</td>
<td>k1pin m3m5</td>
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<tr>
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<td>k1pin m2m8</td>
<td>1,643</td>
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<td>k1pin m7m8</td>
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<td>m6lo6c4</td>
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<tr>
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<td>m4lo3c2</td>
<td>1</td>
<td>k1piu4m6m8</td>
<td>12,500</td>
<td>m7lo8c4</td>
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<td>k1piu4m4m3</td>
</tr>
<tr>
<td>k1piu4m4m3</td>
<td>5,992</td>
<td>m5lo5c3</td>
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</tr>
<tr>
<td>k2pin m1m2</td>
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<tr>
<td>k2pin m1m3</td>
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<td>m8lo7c5</td>
</tr>
<tr>
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<td>k2piu4m8m7</td>
<td>12,499</td>
<td>k2piu4m3m3</td>
<td>1</td>
<td>k1piu4m6m8</td>
<td>10,012</td>
<td>m8lo7c5</td>
</tr>
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<td>k2piu4m8m7</td>
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<tr>
<td>k3pin m2m2</td>
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<td>1</td>
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<td>1</td>
<td>k2piu4m8m7</td>
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<td>m8lo7c5</td>
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<td>10,012</td>
<td>m8lo7c5</td>
</tr>
<tr>
<td>k3piu4m2m2</td>
<td>6,766</td>
<td>k3piu4m7m7</td>
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<td>k3piu4m3m3</td>
<td>1</td>
<td>k2piu4m8m7</td>
<td>10,012</td>
<td>m8lo7c5</td>
</tr>
<tr>
<td>k3piu4m3m3</td>
<td>8,234</td>
<td>k3piu4m3m3</td>
<td>11,457</td>
<td>k3piu4m3m3</td>
<td>1</td>
<td>k2piu4m8m7</td>
<td>10,012</td>
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Table 5.

<table>
<thead>
<tr>
<th>Coalition S</th>
<th>TC(S)</th>
<th>CS(S)</th>
<th>Synergy(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>{f1}</td>
<td>223,200,000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>{f2}</td>
<td>135,493,500</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>{f3}</td>
<td>318,000,000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>{f1, f2}</td>
<td>331,184,000</td>
<td>27,509,500</td>
<td>08</td>
</tr>
<tr>
<td>{f1, f3}</td>
<td>367,165,000</td>
<td>174,035,000</td>
<td>47</td>
</tr>
<tr>
<td>{f2, f3}</td>
<td>342,470,000</td>
<td>111,023,500</td>
<td>32</td>
</tr>
<tr>
<td>{f1, f2, f3}</td>
<td>358,890,000</td>
<td>317,803,500</td>
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Table 6.

<table>
<thead>
<tr>
<th>Factory</th>
<th>Shapley</th>
<th>τ-value</th>
<th>Core center</th>
<th>Least core</th>
<th>ECSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>{f1}</td>
<td>102,520,000</td>
<td>102,550,000</td>
<td>102,910,000</td>
<td>134,895,800</td>
<td>105,934,500</td>
</tr>
<tr>
<td>{f2}</td>
<td>71,010,000</td>
<td>71,300,000</td>
<td>71,570,000</td>
<td>71,884,250</td>
<td>105,934,500</td>
</tr>
<tr>
<td>{f3}</td>
<td>144,270,000</td>
<td>143,960,000</td>
<td>143,320,000</td>
<td>111,023,500</td>
<td>105,934,500</td>
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</tbody>
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Table 7.

<table>
<thead>
<tr>
<th>Coalition S</th>
<th>Shapley</th>
<th>%</th>
<th>τ-value</th>
<th>%</th>
<th>Core center</th>
<th>%</th>
<th>Least core</th>
<th>%</th>
<th>ECSM</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>{f1}</td>
<td>102,520,000</td>
<td>46</td>
<td>102,550,000</td>
<td>46</td>
<td>102,910,000</td>
<td>46</td>
<td>134,895,800</td>
<td>60</td>
<td>105,934,500</td>
<td>47</td>
</tr>
<tr>
<td>{f2}</td>
<td>71,010,000</td>
<td>52</td>
<td>71,300,000</td>
<td>53</td>
<td>71,570,000</td>
<td>53</td>
<td>71,884,250</td>
<td>53</td>
<td>105,934,500</td>
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</tr>
<tr>
<td>{f3}</td>
<td>144,270,000</td>
<td>45</td>
<td>143,960,000</td>
<td>45</td>
<td>143,320,000</td>
<td>45</td>
<td>111,023,500</td>
<td>35</td>
<td>105,934,500</td>
<td>33</td>
</tr>
<tr>
<td>{f1,f2}</td>
<td>146,020,500</td>
<td>44</td>
<td>146,340,500</td>
<td>44</td>
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<td>44</td>
<td>179,270,550</td>
<td>54</td>
<td>184,359,500</td>
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<tr>
<td>{f1,f3}</td>
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<td>72,475,000</td>
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<td>72,195,000</td>
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<td>71,884,300</td>
<td>20</td>
<td>37,834,000</td>
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</tr>
<tr>
<td>{f2,f3}</td>
<td>104,256,500</td>
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<td>104,236,500</td>
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<td>103,866,500</td>
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<td>71,884,250</td>
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<td>100,845,500</td>
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<tr>
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<td>71,300,000</td>
<td>20</td>
<td>71,570,000</td>
<td>20</td>
<td>71,884,250</td>
<td>21</td>
<td>37,834,000</td>
<td>10</td>
</tr>
<tr>
<td>max</td>
<td>146,020,500</td>
<td>52</td>
<td>146,340,500</td>
<td>53</td>
<td>146,970,500</td>
<td>53</td>
<td>179,270,550</td>
<td>60</td>
<td>184,359,500</td>
<td>78</td>
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<tr>
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<td>640,862,000</td>
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<td>640,832,000</td>
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<td>640,842,650</td>
<td>243</td>
<td>640,842,500</td>
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</table>

Table 8.

<table>
<thead>
<tr>
<th>MAD</th>
<th>Shapley</th>
<th>τ-value</th>
<th>Core center</th>
<th>Least core</th>
<th>ECSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shapley</td>
<td>-</td>
<td>001</td>
<td>002</td>
<td>63</td>
<td>72</td>
</tr>
<tr>
<td>τ-value</td>
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<td>-</td>
<td>001</td>
<td>62</td>
<td>72</td>
</tr>
<tr>
<td>Core center</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>61</td>
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</tr>
<tr>
<td>least core</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>64</td>
</tr>
<tr>
<td>ECSM</td>
<td>-</td>
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<td>-</td>
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Table 9.

<table>
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<th>87%</th>
<th>91%</th>
<th>95%</th>
<th>100%</th>
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</thead>
<tbody>
<tr>
<td>f1</td>
<td>Revenue</td>
<td>630,000,000</td>
<td>676,700,000</td>
<td>740,600,000</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>223,200,000</td>
<td>240,070,000</td>
<td>262,820,000</td>
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<tr>
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<td>profit</td>
<td>406,800,000</td>
<td>436,630,000</td>
<td>477,780,000</td>
</tr>
<tr>
<td></td>
<td>Revenue</td>
<td>Cost</td>
<td>profit</td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>f2</td>
<td>1,090,000,000</td>
<td>135,490,000</td>
<td>954,510,000</td>
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</tr>
<tr>
<td>f3</td>
<td>795,000,000</td>
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<td>NA</td>
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<tr>
<td>f1-f2</td>
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<td>337,260,000</td>
<td>1,382,740,000</td>
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<tr>
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<td>936,380,000</td>
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<tr>
<td>f2-f3</td>
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<td>469,490,000</td>
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<tr>
<td>f1-f2-f3</td>
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<td>566,200,000</td>
<td>1,948,800,000</td>
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