AN OPTIMIZATION MODEL FOR CONCURRENT ENGINEERING: INCORPORATING LIFE CYCLE COSTING AND SUPPLY CHAIN DESIGN EARLY IN THE NEW PRODUCT/SERVICE DEVELOPMENT PROCESS

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ABSTRACT

The primary purpose of this paper is to develop a model to help determine optimal product/service, process and supply chain configurations in a concurrent fashion. For that purpose, a concurrent engineering framework and an optimization model that incorporate supply chain design and life cycle costing concepts are developed. In order to demonstrate and validate the proposed model, a numerical example is presented. The model results are compared to those from a sequential design process and indicate that the proposed model can achieve better overall results. Conclusions, implications, and directions for future research are also discussed.

Keywords: Concurrent Engineering, Life Cycle Costing, Mathematical Programming, Optimization, Supply Chain Design.

INTRODUCTION

Increased competition and growing customer demands continue to pressure manufacturing and service firms to improve their products, services, and processes in order to survive in the marketplace. As a result, firms are looking for new product and service designs that will result in a competitive edge and for innovative ways to improve processes that will result in costs savings and higher profits [13].

In addition, spiraling costs and growing environmental concerns associated with product disposal, which can even exceed a product's purchase price, have caused an increasing number of firms to adopt Life Cycle Design (LCD) and Concurrent Engineering (CE) methodologies to achieve improved product designs, reduce total costs, and meet customer demands [28]. For example, General Mills found a way to save over $760,000 annually in product disposal costs by redesigning one of its products and optimizing its manufacturing process and supply chain activities using CE techniques. In a similar case, Medtronic, Inc. integrated CE into the design of one of their medical products and saved over $2.1 million annually by reducing chemical use and waste [1].

Concurrent Engineering can be thought of as an approach to pursuing the different goals involved in New Product Development (NPD). In this sense, the modeling scope focuses on the strategic level of decision-making since product and supply chain design represent infrequent decisions that involve long term forecasting and planning horizons.

The Concurrent Engineering paradigm also involves integrating various NPD development goals in a parallel, rather than sequential fashion. From a decision making stand point, CE results in a more complicated decision-making process that requires the concurrent optimization of a larger and more complex set of objectives subject to a larger set of constraints. Thus, it is likely that multiple conflicting goals will be experienced when using Concurrent Engineering as a NPD tool. For example, the purchasing department may be interested in selecting a low cost supplier to provide certain parts, which may result in lower quality levels. This could create a conflict with the marketing department, interested in developing a product that minimizes the rate of failures in order to maximize customer satisfaction. As such, an appropriate concurrent engineering model should bridge functional boundaries and incorporate different engineering, financial, operations and marketing goals.

The primary objective of this paper is to develop a model that will help determine the optimal product/service, process and supply chain configurations in a concurrent fashion. Despite the publication of several hundred papers on Concurrent Engineering there is little application of mathematical programming or optimization techniques to Concurrent Engineering[1]. Most of the CE research has focused on qualitative analysis, discussion, and techniques. Furthermore, it has been observed that there is a paucity of published research in the area of supply chain modeling at the product development phase [2]. Thus, the purpose of this paper is to help close this gap by developing a quantitative model that addresses the need to simultaneously optimize the product, the process, and the supply chain designs, as well as to model the inherent conflict among the different objectives.

Our research is focused on the following goals:

- To develop a concurrent engineering framework that incorporates supply chain design and life cycle costing concepts.
- To develop an optimization model that incorporates the tradeoffs faced in the development of new products.
- To develop a numerical example in order to demonstrate and validate the model as well as the framework.

The remainder of this paper is organized as follows: A review of the literature related to concurrent engineering is followed by an overview of our proposed framework. Next, we outline the model developed as well as the methodology used in our study. In order to validate our concurrent engineering approach, we examine the mapping of our model solutions with respect to those from the sequential design approach. Subsequently, we show that a concurrent engineering approach can result in a better solution than the traditional design approach. Finally, we conclude with a discussion of the implications and limitations of our research study, and an outline of future research directions.

[1] The current state of the art will be discussed in depth in the Literature Review section.

LITERATURE REVIEW

The topic of concurrent engineering has been studied for several years [3] [6] [18] and continues to be a research topic of interest [5] [19] [24]. Despite several hundred papers on Concurrent Engineering there is little application of mathematical programming or optimization techniques to Concurrent Engineering. In general, most papers have simply provided qualitative insights into the problem.

In that line of work, Eversheim *et al.* developed a conceptual model to support the integration of design and process planning that incorporates performance measures such as responsiveness, time-to-market, cost, quality and life cycle considerations [9]. Similarly, Fixson developed a multi-dimensional conceptual framework that enables comprehensive product architecture assessments. The framework builds on existing product characteristic concepts such as component commonality, product platforms, and product modularity, providing a tool to link product, process, and supply chain design decisions [15]. Tan *et al.* developed a distributed processing framework for evaluating design decisions, detecting and resolving conflicts in design choices made by team members [30]. The method proposed by the authors is based on iterative design changes suggested by individual team members. However, such a system is limited in its ability to optimize a decision over a large number of alternatives, and could require an unreasonable length of time to resolve all of the conflicts.

On the quantitative modeling side, Lamghabbar *et al.* used a mathematical programming technique to find the optimal values of the product and the process design. The objective function was modeled as a quality loss function and the constraints were represented by the production requirements, the product's specification limits, the parts' dimensional limits and the process capability [21]. The authors also performed a parametric analysis of the objective function by applying an interactive multi-objective goal programming technique. Acknowledging that multiple conflicting objectives can be experienced when using CE, Schniederjans *et al.* developed a goal programming approach to model decision making in CE by considering conflicting objective criteria of cost and time. We should note that none of the above described models took into account the product's life cycle or any supply chain consideration.

Overall, CE research has focused on combining production with product design issues. Papers that recognize the need to incorporate supply chain design issues with product and process design (thus creating a three-dimensional challenge) have started to emerge recently. Dowlatshahi (1996) had noted that little or no work is being done on the interface of product design and logistics [7]. Subsequently, Fisher suggested matching the supply chain with the product structure [14] and Dowlatashi (1999) developed a conceptual interface for Design for Logistics, focusing on facilitating the collaboration between the design and the logistics functions in order to encourage logistics involvement in the early phases of product design in a concurrent engineering environment [8]. Appelqvist *et al.* developed a conceptual framework for supply chain decision making and proposed an approach to integrate product life cycle modeling systems. The authors also reviewed the current modeling practices through a literature survey. Their main finding was a lack of published research in the area of supply chain modeling at the product development phase, even though it is in the product development phase where the majority of product life-cycle costs are determined [2]. In this line of research, the idea of Three-Dimensional Concurrent Engineering (3D-CE) was proposed by Fine [11]. 3D-CE represents a framework for product, process and supply chain design [12], which encourages the concurrent determination of the product, the manufacturing process and the suppliers. The framework acknowledges that with today's fast industry clock-speeds, every new product constitutes a high-risk, short-life project [20].

From a quantitative modeling perspective, Feng *et al.* formulated a stochastic integer programming model based on quality loss function and different process capability indices that enables the simultaneous determination of tolerances in the product design as well as the selection of suppliers for the various components of the product [10]. Similarly, Fine *et al.* developed a 3D-CE optimization model that enables the representation of the interrelations among multiple objectives [13]. The authors proposed a goal-programming modeling approach and demonstrated the model through a discussion of integrality versus modularity in product and supply chain designs. However, none of the models above takes into account life cycle costing or considered the forward supply chain.

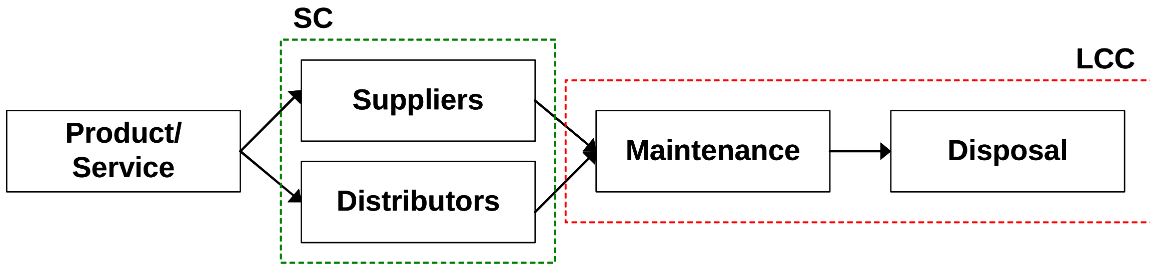
The relatively few articles found in the literature focus on using multiple objective criteria in solving concurrent engineering problems. With the exception of the last two references, the rest of the 3D-CE papers simply provide qualitative insights into the problem. Furthermore, the scope of our model is more extensive than those of the papers described above, since none of the studies offers a quantitative methodology that takes into account a product lifecycle approach and its associated life cycle costs in order to analyze the various 3D-CE tradeoffs. Nevertheless, common ground is found in the utilization of optimization techniques in CE as well as the use of multicriteria decision methods and embedded models.

In summary, our paper is aimed at developing a quantitative model to implement the principles of the concurrent engineering paradigm, which has been discussed primarily in a qualitative manner in the literature. This paper represents an attempt to close the gap between qualitative and quantitative modeling through the development of a comprehensive quantitative model that includes a life cycle costing approach as well as the modeling of the forward supply chain.

FRAMEWORK

This research paper is in part motivated by the mistakes made by developers of new products in bringing those products to market rapidly and effectively. Traditionally, decisions on the development of new products are taken in a serial pattern (See Figure 1). First, a product design is selected from a set of alternative designs, taking into account marketing, financial and engineering goals. Next, the selected design is usually transferred to the production planning department which is in charge of developing the manufacturing plan taking into consideration operational goals such as capacity utilization and production balancing. Finally, the product and the production design decisions are submitted to the logistics department which determines the different supply sources. However, as pointed out by Gunasekaran, the designs produced by this serial pattern are subject to a number of problems [18].

FIGURE 1
Traditional Sequential Design Approach



In the first place, the process is slow and, consequently, market opportunities may be missed. A key challenge for corporations today is the increasing velocity of change (i.e., clockspeed) in the business environment. Mendelson *et al.* found that higher industry clockspeed is associated with faster execution in product development and manufacturing, such as shorter development times [22]. As a higher level of industry clockspeed means faster product obsolescence and more rapid changes in supply conditions, we should expect the pace of product development to accelerate. Thus, firms will need to revise their design processes and act faster in order to seize opportunities and, ultimately, survive.

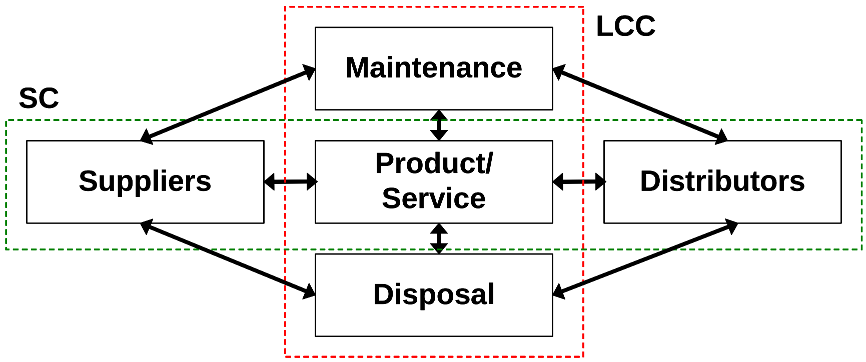
At the same time, the serial process discussed above results in sub-optimal decisions, since the decisions made at each stage represent, at best, locally optimal choices. In this sense, careful consideration must be given to addressing the impact that design decisions will have on the rest of a product's life cycle because, even though the actual product design cost usually accounts for only 5 to 10% of the total life cycle cost, the decisions made at the design stage usually determine 70 to 80% of the total life cycle cost [6]. For example, sales margins may easily be offset in the downwards supply chain by the costs of product returns, which can take various forms: from consumer convenience returns to repair and maintenance returns, or end-of-life returns.

In addition to returns, companies are increasingly expected to take responsibility for the full life cycle of their products including the disposal, which extends the impact of the decision made at the design stage far beyond the purchase [17]. The European Union, for example, recently adopted the Waste Electrical and Electronic Equipment (WEEE) act that makes producers responsible for environmentally friendly disposal solutions and for organizing product take-back from consumers at no cost. One should expect this trend to expand to other economic regions. As a result, companies such as Sony expect that changes in the regulations may cost as much as 1-2% of revenues, a significant number considering the small profit margins of some products [20].

Furthermore, the development of new products/services may present companies with a particularly difficult challenge. That is, some companies will need to develop not only a new product and a new process to manufacture it, but also a new supply chain to feed that process and distribute the product. As a consequence, those companies will need to take into account additional strategic supply-chain issues at the product design stage, such as the level of dependency resulting from sourcing decisions, i.e., the level of risk incurred by a firm as a consequence of its reliance on external suppliers.

Recognizing the above-mentioned flaws of the sequential design process, we propose a concurrent engineering (CE) framework that takes into consideration all of the above mentioned costs at the product and supply chain design stages (See Figure 2).

FIGURE 2
Proposed Concurrent Engineering Framework

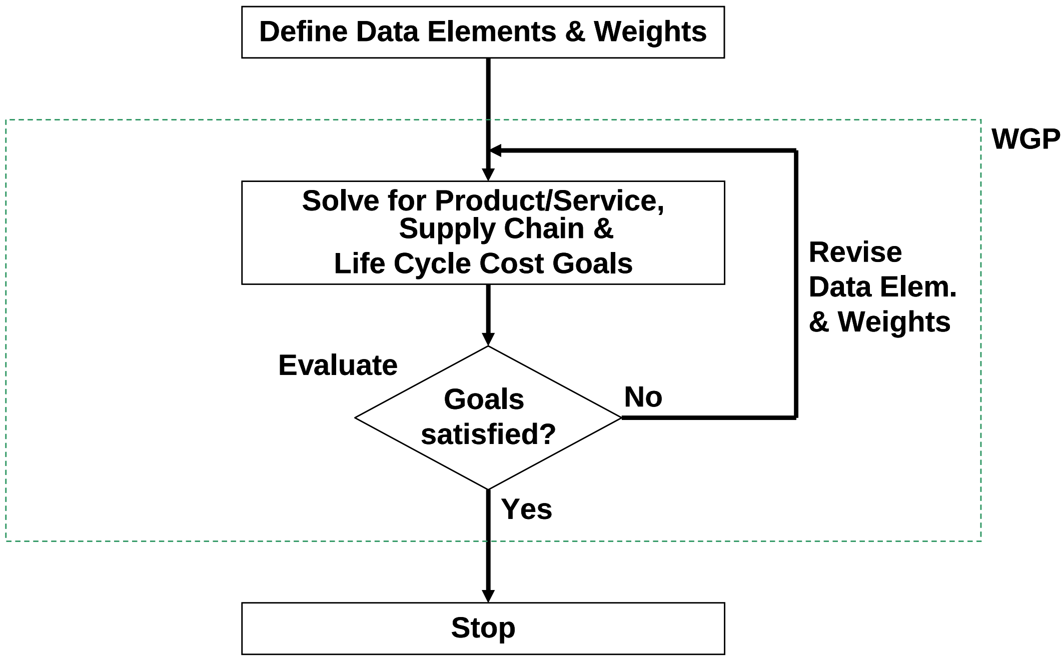


Our proposed concurrent engineering framework requires not only that design decisions are made in parallel and that different product and process issues be incorporated into the early stages of design [13] but also represents an approach to deal with the above discussed needs to adopt a life cycle cost approach and to incorporate strategic supply chain considerations in the design stage. In essence, the goal of our concurrent engineering framework is to ensure that all the impacts of the decisions are considered at the design stage, before actual full-scale production begins.

MODEL

Based on our proposed framework, we developed an optimization model that employs a Weighted Goal Programming (WGP) technique to simultaneously solve for the best configuration of product/service and supply chain (See Figure 3). Since designing a new product/service requires one to consider a large number of performance measures and trade them off against one another, Schniederjans *et al.* suggested that multicriteria methods should be used in new product development planning [27]. We used goal-programming (GP) as the modeling tool because it represents a flexible technique that can easily accommodate a large number of objectives and it has a large body of reported implementations in different modeling areas [4] [26] [29].

FIGURE 3
Weighted Goal Programming (WGP) Model



In their CE model, Fine, et al. focus on five goals common to product design and supply chain decisions—fidelity, cost, lead-time, partnership, and dependency—and use mathematical programming to determine an optimal solution. Their measure of fidelity describes "the degree to which the product element's design conforms to the tasks it is intended to perform**,"** and their measures of partnership and dependency describe aspects of supply-chain risk and reliance on external suppliers [13].

However, a model that supports CE should also take into account a variety of costs and other performance measures associated with the various stages of the product life cycle. For this reason, our model includes various product design, supply chain, and life cycle cost goals inherent to the new product development process seeking to evaluate the impact of choosing a certain design alternative. The model takes into consideration different interactions between goals, such as the interaction between the customer fit and warranty costs, demonstrating the advantages of including data related to field failures at early stages of the NPD decision making process.

In order to accomplish our research objectives, we extended the model proposed by Fine, et al., transforming it into WGP model that includes not only product design and supplier related measures, but also forward supply chain and life cycle costs measures. In our product design decision, we seek to achieve a certain measure of fidelity while achieving specific marketing and manufacturing/assembly cost goals. Our supply chain design decision include target goals for lead-time, the number of suppliers, and the number of distributors while also taking into account different supply chain management cost goals. Finally, in our life cycle cost decision, we take into consideration specific goals related to maintenance, warranty, and disposal alternatives.

METHODOLOGY

To explore the validity of implementing a comprehensive concurrent engineering approach and compare it to the use of a sequential design approach, we developed an experiment that explicitly quantifies the tradeoffs among the model components that were described in the previous section.

Specifically, we developed a numerical example in order to demonstrate and validate the proposed model and framework. The experiment consisted of three parts. First, we constructed 30 instances of a NPD data set where the values of the parameters in each instance were randomly generated.

Second, using the Premium Solver Platform from Frontline Systems, Inc., we solved each instance using the two different approaches, first using a traditional sequential approach and then using our CE goal programming model. In the sequential design approach (see Figure 1), the different decisions were modeled as a sequence of three goal programs. Thus, the product/service design decision was addressed in the first place. Based on the product/service configuration selected in step one, the supply chain decisions were tackled next. Finally, based on the product/service and supply chain configurations selected in steps one and two, the maintenance and disposal decisions were considered last. The results of those decisions were then combined adding together the different life cycle costs (i.e., Total Life Cycle Costs = Design + Production + Maintenance + Disposal costs), and also adding together the deviations from the different supply chain and product/service life cycle goals.

In the case of our concurrent engineering model, we addressed all those decisions concurrently, determining the total deviation from the supply chain and product/service life cycle goals as well as the total life cycle cost simultaneously. Finally, we compared and analyzed the results of each approach in order to draw conclusions and implications.

RESULTS

The results of our model along with the results obtained from the sequential design approach are displayed in Table 1. A detail of the results obtained for each approach can be found on Appendix A.

TABLE 1
Summary of results for the concurrent engineering approach vs. the sequential design approach

	Approach	
	CE	**Sequential**
Average Total Life Cycle Costs **(Design + Production + Maintenance + Disposal costs)**	\$1,596,991.00	\$1,806,654.00*
Average Deviation from Goals **(Supply Chain and Product/Service Life Cycle Goals)**	7.15	9.39*

* Indicates statistically significant differences from the CE approach at the α =.05 level (n = 30)

The outcomes of the experiment indicate that the CE model yields better solutions, on average, than the traditional sequential design model. Specifically, our proposed CE approach resulted in average total life cycle costs that were 11.61% lower than those obtained using the sequential approach. In addition, our proposed CE approach resulted in an average deviation from the goals that was 23.77% lower than the one obtained using the traditional sequential approach.

CONCLUSIONS AND IMPLICATIONS

The objective of this study was to develop a model to help determine optimal product/service, process and supply chain configurations in a concurrent fashion. For that purpose, we developed a concurrent engineering framework and an optimization model that incorporate supply chain design and life cycle costing concepts and applied it to a new product development example. The results of our model were then compared to the results from a sequential design approach. A number of relevant implications arise from this research study.

First, our results indicate that the concurrent engineering model provides solutions that are at least as good as the solutions obtained using the sequential design approach. The results clearly stress the importance of incorporating strategic supply chain considerations and adopting a life cycle cost approach early in the design stage.

On the other hand, the serial design process results in sub-optimal decisions because the decisions made at each stage represent locally optimal choices. Therefore, careful consideration must be given to addressing the impact that design decisions will have on the rest of a product's life cycle, as indicated by our results. By ensuring that all the impacts of the decisions are considered at the design stage, before actual full-scale production begins, our concurrent engineering model provides a way to overcome the limitations of the sequential design process.

Overall, our model represents a simple and suitable tool for enhancing and facilitating the development of new products and services. The model, which is unique in terms of incorporating supply chain design and life cycle costing concepts to solve new product/service development problems, can be applied to different manufacturing and services sectors. In addition, our concurrent engineering approach permits the inclusion of as many objectives as a firm requires.

Essentially, our model can be extended to any number of objectives by simply incorporating additional data elements for each objective.

LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Our model is subject to a limitation inherent to planning models: inaccurate parameter data can invalidate its informational benefits. An additional limitation of the model is its complexity since it requires the collection and processing of a substantial parameter database.

Additionally, the case data represents a simplified model in terms of the number of product and supply chain configurations. Even though the data used constitutes a representative, but certainly not exhaustive, new product design problem, the reduced scope and complexity is a limitation to our model's ability to accurately serve as a generalizable model. Further research using data of sufficient size and scope should be done in order to fully validate the proposed model. An ideal direction for future research would be to develop a case study in which the method will be implemented using real data.

The technique we used as our modeling tool was goal programming. This is a widely used multi-criteria decision making technique that has been employed in many application areas. However, we should note the potential weaknesses of this technique [29]. In particular, its sensitivity to changes in the goal values that are determined subjectively prior to the implementation of the model itself as well as the sensitivity to changes in the corresponding goal weights [23] [25]. As a consequence, the users of the WGP model should pay attention to the values they determine for the goals and weights. The goal programming literature offers alternative procedures for the determination of weights, such as the one proposed by Gass [16], which uses analytical hierarchy process to quantify weights, or the ones identified by Tamiz et al. [29].

Another interesting alternative to our WGP model would we to develop a multiobjective optimization model for concurrent engineering that incorporates fuzzy logic to represent different model components. The use of fuzzy logic to represent objectives as fuzzy membership functions or fuzzy sets is a suitable method for solving multiple criteria decisions that allows the decision maker to set preferences for goals when there is vague and unclear information.

Finally, different extensions to our concurrent engineering model can be identified. Since our WGP model is quite flexible, it can be extended to include different combinations of new product development and supply chain design goals in a concurrent fashion. In this sense, the model could be extended to include expected demand parameters (a forecast that would be generated by the marketing department using a forecasting model) to calculate expected profits. The model could also be extended to include other aspects that are relevant to in-house production (such as capacity utilization) in order to analyze the usage of the available production resources.

Overall, our preliminary results validate the concurrent engineering model and warrant further investigation. We hope that the present paper will represent the initial step towards the implementation of the aforementioned extensions.

APPENDIX A

The solutions for each model are detailed in the following table.

	Approach			
	Concurrent Engineering		Sequential Design	
Replication #	Total Life Cycle Costs	Deviation from Goals	Total Life Cycle Costs	Deviation from Goals
1	$1,670,249.47	7.21	$1,878,595.66	9.50
2	$1,630,820.95	6.50	$1,833,799.48	9.20
3	$1,622,929.48	7.09	$1,869,719.98	9.00
4	$1,400,507.88	7.38	$1,739,548.05	9.19
5	$1,592,722.92	7.44	$1,789,609.58	9.53
6	$1,631,773.21	6.70	$1,827,208.62	8.67
7	$1,651,077.69	7.16	$1,864,770.68	8.86
8	$1,661,916.16	7.06	$1,730,541.63	9.24
9	$1,572,606.46	7.35	$1,714,113.40	9.31
10	$1,617,142.09	7.43	$1,769,880.30	9.52
11	$1,606,803.40	7.37	$1,846,919.34	9.63
12	$1,673,215.56	6.67	$1,880,801.16	8.86
13	$1,636,175.25	7.21	$1,878,289.39	9.90
14	$1,639,403.64	7.09	$1,785,022.73	9.28
15	$1,539,095.84	7.07	$1,801,536.67	9.83
16	$1,665,761.60	7.27	$1,847,678.08	9.88
17	$1,661,624.09	7.47	$1,748,259.40	9.62
18	$1,272,984.36	7.02	$1,688,839.33	9.73
19	$1,580,070.40	7.20	$1,710,999.69	9.29
20	$1,329,905.90	6.98	$1,843,196.57	9.29
21	$1,607,250.80	7.33	$1,827,940.21	9.50
22	$1,625,599.43	7.48	$1,683,773.50	9.34
23	$1,581,139.93	7.43	$1,820,209.98	9.65
24	$1,631,230.18	7.42	$1,863,962.87	9.31
25	$1,684,210.56	7.49	$1,862,536.84	9.69
26	$1,531,088.34	7.43	$1,632,392.78	9.57
27	$1,603,467.21	7.29	$1,885,696.06	8.71
28	$1,678,685.74	7.11	$1,861,735.62	9.69
29	$1,596,295.01	7.11	$1,870,485.55	8.93
30	$1,613,965.61	5.90	$1,841,567.76	9.88

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