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Using functional metrics to facilitate designing collectively exhaustive mutually exclusive systems in the context of managing return on investment

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Abstract

The objective of this paper is to test two hypotheses in the context of managing return on investment (ROI): (1) that a meaningful functional metric (FM) assigned to every functional requirement could facilitate the design of collectively exhausting mutually exclusive (CEME) systems and (2) that parent functional metrics should equal the sum of their children. FM at every level can facilitate objectively improving a system as well as tracing the root cause of underperformance within a system. Three attempts at designing a quantitative CEME system are critiqued to support or refute the hypotheses. The design attempts increasingly feature FMs with each iteration. Examination of the design attempts supports the hypotheses, however it is unclear whether the hypotheses would prove true outside of the context of ROI. The possibility of incorporating physical metrics into every level of future designs is discussed. This paper is intended to lead to future work testing a metric based decomposition hypothesis.

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Keywords: Return on investment; functional metrics, collectively exhuastive mutually exlusive

1. Introduction

The objective of this paper is to test two hypotheses in the context of managing return on investment (ROI):
(1) That a meaningful functional metric assigned to every functional requirement (FR) could facilitate the design of collectively exhaustive mutually exclusive (CEME) systems.
(2) That parent functional metrics should equal the sum of their children.

In this paper, metrics are defined as quantifiable measures used to determine the degree of success of a system or process. A functional metric (FM) indicates how well a FR satisfies a customer need (CN). A physical metric (PM) is defined as the adjustable dimension of a design parameter (DP) responsible for controlling a FR. This paper is inspired by a work-in-progress design that has been satisfactorily unsuccessful to date at decomposing a quantitative CEME system. Metrics were intended to be assigned to each FR and DP. It is worth noting that "manage ROI" was chosen over "maximize ROI" in the objective. Suh [1] and Cochran [2] use maximize as the verb in FR 0. Thompson [3] writes that maximize is selection criteria when choosing between possible DP options. Maximizing ROI without a specified time interval can be harmful to a company. Actions taken to maximize short term ROI can hurt long term ROI. Manage can be a more appropriate verb when there might be times that accepting a lower ROI in one time interval to increase ROI in another can be in the company's best interest.

"If a system or process cannot be measured then it cannot be objectively improved" (Lord Kelvin). A system with metrics can be compared against benchmarks. These benchmarks can be measurements of some previous state of the system, a desired goal, or best in class measurements of a competitor. Without being able to quantitatively measure the metrics at a system's current state, it cannot be objectively determined whether the system is improving or the amount of improvement.

Having FMs in a system can facilitate translating CNs into the subsequent domains. Axiomatic design begins with the customer domain. Customers express ideas that become CNs, which they require in a process or system [1]. When

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meeting with customers over time, new CNs can be expressed late in the design phase. Cochran [4] writes how this can leave a design susceptible to "requirement soup." This occurs when every new idea becomes a CN with no explanation of where they fit into the current design or the importance of one CN in relation to another. Having metrics at every level can facilitate determining where CNs belong in a design, regardless of when the CN is expressed during the design phase, by what metrics they affect.

Without metrics at every level, when the system is underperforming, it can be difficult to trace the cause [5]. An integral part of continuous improvement should be identifying and removing the root cause of dysfunction in the system. FMs at every level can facilitate identifying the cause of dysfunction.

Metrics at every level can improve long term ROI. By measuring only financial metrics at the executive level, focus is placed on efficiency. Innovation processes, which can have a negative short term effect on ROI but potentially improve long term ROI, can be avoided as a result [6]. By having FMs at every level, focus is place upon efficiency and effectiveness [7].

1.1. State of the Art

Brown [8] writes that a good hierarchical decomposition must be CEME. MECE meaning "mutually exclusive, collectively exhaustive" is a method designed for facilitating the framing of a problem. The goal is to reduce the parts of a problem to non-overlapping issues to prevent leaving out relevant issues [9]. Axiomatic design evolved this method into CEME min, which uses the minimum number of FRs while remaining collectively exhaustive and mutually exclusive [10]. They write that the sum of the children FRs and DPs must equal the parent for a CEME decomposition.

The use of metrics to measure the success of systems is not a new phenomenon. Until recent decades however, the focus has been on measuring top level financial metrics with little measurement at the performance level. Bruns [11] writes that for centuries the level of a system's success has been based on financial metrics. An important milestone was the creation of the return on investment metric by DuPont in 1912. Kaplan [6] writes that almost all of the practices for measuring cost and financial success were developed by 1925. Since then, there were no major innovations in performance metrics until the 1980s. Due to the competitive manufacturing environment of the 1980s, there became a growing belief that top level financial metrics alone were not sufficient for improving or controlling systems [12].

As a result, organizations began investing effort into developing performance measurement systems. The most commonly used system was the balanced scorecard (BSC) [13, 14]. This system was designed to link what was determined to be the four important perspectives in a business: financial, customer satisfaction, innovation and performance. Each perspective has multiple goals within, and each goal has functional metrics to be measured. Kennerley et al. [15] write that data gathered by the Balanced Scorecard Collaborative suggest that over fifty percent of the largest businesses in the USA adopted the BSC by the end of 2000.

Another system worth noting is The Strategic Measurement and Reporting Technique (SMART) pyramid [16]. Unlike BSC, SMART was designed as a performance measurement system that decomposes corporate objectives down to lower level goals versus viewing metrics by perspective. The system links performance metrics to top level metrics, prioritizes both efficiency and effectiveness but excludes continuous improvement [17].

Even in professional sports, lower level performance metrics have been linked to traditionally measured top level metrics to improve the level of success of the top level function. Lewis [18] writes about the failure within professional baseball to identify the right metrics. For decades, teams had bought players in an attempt to increase wins using statistics such as batting average and runs batted in. Statistical analysis showed that on base percentage had a higher correlation with runs scored, which in turn determines wins. With this information, the 2002 Oakland Athletics were able to win the most games of any team in the league during the regular season, despite paying the third lowest salary to their roster. They also broke the American League record for most games won in a row at 20 wins.

Metrics have been used in axiomatic design previously. Suh [1] gives many examples in his book of decompositions with metrics for the FRs and DPs. One simple example is a hubcap design in which the FR is retention force and deflection is the DP. Even though he only writes of it in respect to the FR design range for determining the DP design range, the force of retention can be measured as a FM. Similarly the deflection can be measured as a PM.

In the context of ROI, Suh [1] proposed that ROI can be decomposed to three main FRs: (1) increase sales revenue, (2) minimize cost and (3) minimize investment. His design decomposes the functional metric equation for FR 0, ROI = (Sales - Cost / Investment). The next level of FRs and DPs are used to control each variable in the equation independently. Manufacturing System Design Decomposition (MSDD) was similarly designed using the same 3 three top level FRs as Suh [1] used to satisfy the goal of maximizing return on investment [2]. Collective System Design (CSD) is a method based on axiomatic design theory [4]. This system provides a behavior and process for collective agreement during a company's conversion to lean, to achieve long term sustainability. This includes assigning metrics to FRs and DPs.

1.2. Approach

Three attempts were made to design an order acceptance system using axiomatic design. This is a system for deciding which orders a engineer to order (ETO) manufacturing company should prioritize working on, when the workload exceeds the available capacity. The company's goal is to achieve the highest potential ROI. For these design attempts, the ETO company is considered the customer. Each attempt has been unsuccessful at designing a quantitatively justifiable CEME system. Each design attempt iteration increasingly features FMs to facilitate and add value to the design. The process for each design attempt will be explained. The possible reasons for failure in each design attempt will be discussed. It will be discussed whether the attempts support or refute the paper's hypotheses.

Similar to BSC and SMART, the design attempts feature FMs. Unlike BSC, a top down hierarchy is used. Similar to SMART, the design attempts decompose higher level metrics from the top level financial metrics down to the lower level performance FMs. However, the design attempts include continuous improvement.

The design attempts are similar to Cochran's [2] MSDD method and similar to Suh's [1] ROI decomposition method. However, the current method uses a different equation ((gain - cost) / cost) [19]. Also unlike their systems, the third attempt has FMs to be measured at each level versus the top levels.

Similar to Brown [8] and Dickinson et al. [10] each design is an attempt at a CEME system. Unlike in their works, the approach in the third design attempt provides a metric based method for designing CEME decompositions. Parent FMs appear as mathematical equations or expressions. These FMs decompose into children FMs which independently control each variable in the equation or expression. This process will continue down to lower level independent variables. FR DP pairs are designed to control each FM independently. This method serves as a quantitative justification for CEME.

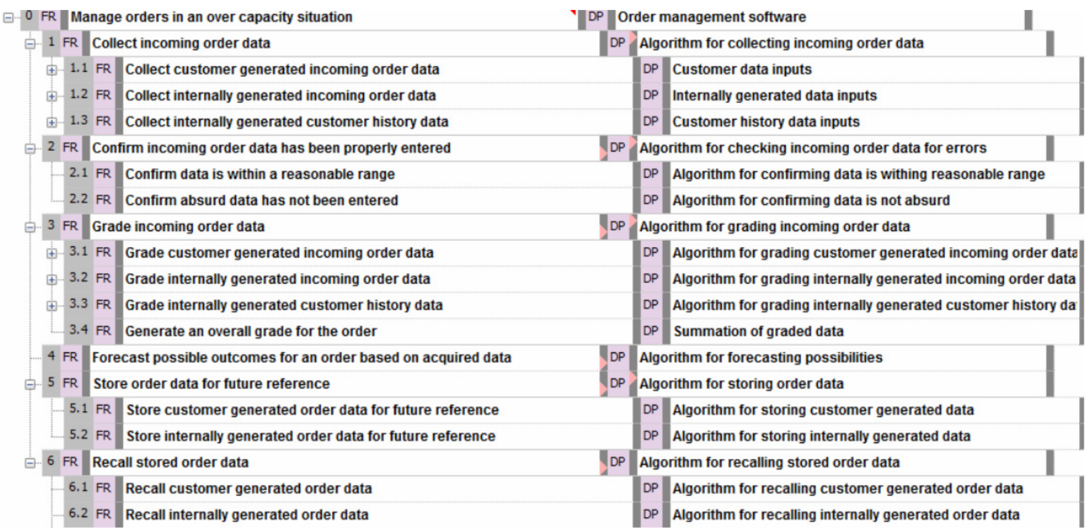
2. Design Attempts

2.1 FRs and DPs with no metrics

This decomposition (Figure 1) was done before the use of FMs, which were added later. FR 0: "Manage orders in an over capacity situation". The first level was designed using a theme based on three customer needs: (1) evaluate incoming orders [FR 1-3] (2) forecast possible outcomes for an order [FR 4] (3) store the data for future use [FR 5-6]. There was difficulty designing a system in which every CN translated to a FR or DP while remaining CEME.

This decomposition was the result of collecting multiple lists of customer needs over time and suffered from "requirements soup." Also, even though this system was designed to manage orders, there is no way to tell how successful the order management software is at satisfying FR 0. Choosing a FR 0 that does not have an indicated preference for which direction it should go in is likely a cause for difficulty with this design. Having a metric would facilitate determining how successfully FR 0 is being satisfied. A possible logical FM for this FR 0 might be the percent or number of orders being managed, but this does not add much value to the customer.

The value to the customer is not in the managing of orders, but instead in increasing ROI. The order management software is the tool for doing so. Increase or control ROI might be a better FR 0 with the order management software / system as DP 0.



No.	FR	DP
0	Manage orders in an over capacity situation	Order management software
1	Collect incoming order data	Algorithm for collecting incoming order data
1.1	Collect customer generated incoming order data	Customer data inputs
1.2	Collect internally generated incoming order data	Internally generated data inputs
1.3	Collect internally generated customer history data	Customer history data inputs
2	Confirm incoming order data has been properly entered	Algorithm for checking incoming order data for errors
2.1	Confirm data is within a reasonable range	Algorithm for confirming data is withing reasonable range
2.2	Confirm absurd data has not been entered	Algorithm for confirming data is not absurd
3	Grade incoming order data	Algorithm for grading incoming order data
3.1	Grade customer generated incoming order data	Algorithm for grading customer generated incoming order data
3.2	Grade internally generated incoming order data	Algorithm for grading internally generated incoming order data
3.3	Grade internally generated customer history data	Algorithm for grading internally generated customer history da
3.4	Generate an overall grade for the order	Summation of graded data
4	Forecast possible outcomes for an order based on acquired data	Algorithm for forecasting possibilities
5	Store order data for future reference	Algorithm for storing order data
5.1	Store customer generated order data for future reference	Algorithm for storing customer generated data
5.2	Store internally generated order data for future reference	Algorithm for storing internally generated data
6	Recall stored order data	Algorithm for recalling stored order data
6.1	Recall customer generated order data	Algorithm for recalling customer generated order data
6.2	Recall internally generated order data	Algorithm for recalling internally generated order data

Fig. 1: Design attempt that suffers from "requirements soup."

ID	FR	DP	FM
0	Increase potential ROI during over capacity situations	Robust order acceptance system	ROI*PCS*(1/abs(1-delta))
1	Reduce orders to one number that favors the higher probability of higher potential ROI	Order quanitification system	ROI*PCS
1.1	Collect critical incoming order data	Office traveller	
1.1.1	Collect function based incoming order data	System for collection of function based data	
1.1.2	Collect PCS based incoming order data	System for collection of PCS based data	
1.1.3	Collect ROI based incoming order data	System for collection of ROI based data	
1.2	Grade critical incoming order data	Software for grading incoming order data	
1.2.1	Grade PCS based incoming order data	Equations for grading PCS based incoming order data	
1.2.2	Grade ROI based incoming order data	Equations for grading ROI based incoming order data	
1.2.3	Generate an overall grade for the order	Summation of the generated grades	
2	Improve order forecast data accuracy over time	Uncertainty reduction system	Delta
2.1	Collect completed critical after order data	System for collecting critical order data	
2.1.1	Collect PCS based completed order data	System for collecting PCS based completed order data	
2.1.2	Collect ROI based completed order data	System for collecting ROI based completed order data	
2.2	Compare incoming estimates to after order recorded values	System for comparing estimates to actual data	

Fig. 2: Design attempt using FMs at the top two levels.

This design led to several observations. The customer does not necessarily know how the full decomposition should look, but they might have a metric they internally measure. As a result, they might request needs that they believe affect the top level metric but in fact do not. Also, the customer might fail to request necessary parts of CEME system. Using a top level functional metric could facilitate determining whether requested CNs should be a part of the design and if there are missing FRs that belong in the design.

The observations made from this design support the first hypothesis that FMs could facilitate designing systems to manage ROI.

2.2. Functional metrics at the top levels

This decomposition (Figure 2) was made using FMs at the top two levels. FR 0: Increase potential ROI during over capacity situations. This was an attempt to design a CEME system, using a quantitative decomposition theme, without causing information overload. Kaplan [13] writes that information overload can result from having too many metrics to monitor. He writes that managers might benefit by having a few critical metrics to focus on. The top level FRs were determined with the goal of controlling the top level metrics. The lower level FRs and DPs were translated from customer needs.

The top level metric was initially ROI. After decomposing FR 0 down one level, it became clear that ROI was not a collectively exhaustive top level metric. Melnyk [20] writes that a metric should be any measure that adds value to the system. ROI was not the only value adding metric in this system.

When an ETO company receives an incoming order, they make estimates on how long tasks will take and what the costs will be. These estimates are made using expert opinion and are likely to differ from the actual costs during the manufacturing process. Reducing "delta," which is defined as the difference between the estimated and actual costs provides value.

Achieving the potential ROI is contingent upon being able to both successfully fill the order and deliver the product on time (PCS). Successful completion is not a guaranteed outcome. The value of an order changes with the change in the probability of achieving the potential ROI. There is value in knowing that probability. The top level metric was adjusted to be the product of ROI, PCS and 1/ (1+delta).

ID	FR	DP	FM
0	Continuously improve the competitiveness of an ETO company	Work prioritzation system that evolves	(Probable ROI / (1+delta)) / time
1	Determine which work to prioritize	Value adding resource allocation	Probable ROI = ROI * Probability of achieving that ROI (PCS)
1.1	Determine the value of orders periodically	Order quantifcation system	ROI *PCS
1.1.1	Determine the probability of successfully completing an order on time	Order difficulty analysis	PCS = (1 / Complexity) * f(Hours needed)
1.1.2	Determine the ROI	Estimations that quanitifies ROI related attributes to one number	ROI = ((Gain - cost) / cost)
1.2	Determine the impact of fulfilling a new order on the current batch	Change in average order value vs resources to be consumed	ROI*PCS vs. Average ROI*PCS
1.2.1	Determine available resources	Remaining capacity	Available resources = time + machines + raw material
1.2.1.1	Determine available time windows	Due date ranking	Available time windows
1.2.1.2	Determine available equipment	Equipment allocation	Available machines
1.2.1.3	Determine available raw materials	Raw material allocation	Available raw material
1.2.2	Determine the value of accepting the order	Comparison of order ROI to average order ROI	Probable ROI of the order vs. Average ROI
1.2.3	Determine resources need to complete an order	Comparison of requirements to available resources	Required resources vs. available resources
1.2.4	Determine the ability to increase time window	Negotiation with customer	Time
1.2.5	Determine possible reneges	Exclusion due to low probability of success of fulfilling order	ROI * PCS
1.2.6	Determine the costs of re-prioritization	Time lost re-prioritizing work	Cost of re-prioritization
2	Continuously improve the accuracy of estimates	Heuristic analysis of past estimates	Delta = (Inaccuracy / number of uses)
2.1	Increase use of order acceptance system	Employee buy-in	Number of uses
2.2	Reduce estimation inaccuracy	Processes for eliminating the root cause of inaccuracy	Inaccuracy = Regular inaccuracy + irregular inaccuracy
2.2.1	Reduce regular inaccuracy	Estimation bias elimination	Habitual inaccuracy = Trending Inaccuracy + Consistent inaccuracy
2.2.1.1	Reduce trending inaccuracy	Future trend research	Trending inaccuracy = changes in material cost inaccuracy + market chance in
2.2.1.2	Reduce consistent inaccuracy	System for reducing consistent inaccuracy	Consistent inaccuracy = Inaccuracy in material estimates + inaccuracy in time
2.2.2	Reduce irregular inaccuracy	Elimination of the root cause of disruption	Irregular inaccuracy = Disruption based inaccuracy + order inaccuracy
2.2.2.1	Reduce disruptions	Highly predictable processes	Disruptions inaccuracy
2.2.2.2	Reduce future order revenue inaccuracy	Research into the customer's ordering patterns	Future order revenue inaccuracy

Fig. 3: Design attempt with FMs assigned to FRs at all levels

When an ETO company receives an incoming order, they make estimates on how long tasks will take and what the costs will be. These estimates are made using expert opinion and are likely to differ from the actual costs during the manufacturing process. Reducing "delta," which is defined as the difference between the estimated and actual costs provides value.

While decomposing the lower levels, there was no clear theme due to not using lower level FMs that make up the ROI, PCS and delta terms. Because of this, elements like capacity were not considered, even though, in retrospect, capacity is a necessary consideration when accepting an order. FR1: "Reduce orders to one number" was considered acceptable at the time. Using FMs at every level, it would have been obvious that focusing solely on reducing orders to one number as the way for improving ROI was not CEME. Another issue in this design is that if only top level metrics are measured, there is no way of knowing the cause of dysfunction if the system underperforms as Austin [5] wrote.

These findings led to the hypothesis that having FMs at every level could facilitate designing systems to manage ROI. This design supports the hypothesis that children FMs should sum to equal their parent one level down. This design neither supports nor refutes the hypothesis at the lower levels of the decomposition.

2.3. Functional metrics for every FR

This design (Figure 3) has been decomposed with FMs assigned to FRs at all levels. FR 0: Continuously improve the competitiveness of an ETO company. PMs have not been assigned in this design but will be attempted in a future iteration. **Probable ROI / (1 + delta)** was chosen as the top level FM from what was learned in earlier designs. Probable ROI is the product of ROI and PCS.

Current findings indicate that FR 1.2 and its children are necessary parts of a CEME design. However, FR 1.2 is not decomposing as cleanly as the other parts of the design. Each attempt to re-organize them reduces the number of outlying children, and so it is likely that the children of FR 1.2's correct place in the decomposition just has not been determined yet. Other than FR 1.2, all the children FMs sum to equal the parents.

This decomposition provides value to the customer by offering independent control of each variable that at the lower levels that affect the top level metric. Also, there is value to a customer if the system facilitates tracing the root cause of underperformance; having FMs at every level provides this. Current findings indicate this design iteration could be close to being a CEME system; however, there is room for improvement for tracing root causes of underperformance to DPs. If the FRs are not being controlled within the acceptable range, it could facilitate tracing the root cause to the DP.

This design supports the hypothesis that FMs can facilitate designing a CEME system. This design supports the hypothesis that children FMs should sum to equal their parent.

3. Discussion

The current findings indicate that FMs at every level of the design can facilitate designing a quantitatively CEME system. FMs have been used in the third design attempt to decompose a CEME system. Each level of FMs is determined using the FM from the level above. Each child FM controls a variable from the parent FM equation or expression. This can be repeated down to lower level independent variables or until the method for determining those variables is obvious. It is unclear how well this would work outside the context of managing ROI.

The current findings indicate that children FMs should sum to equal the parent, if sum is defined as combine instead of solely as addition. This has been an understood concept in previous works dating back to Suh [1] and Cochran [2], seeing as their top level equation features subtraction and division. However when talking quantitatively, to avoid confusion, it might be more accurate to say that the children combine to equal the parent.

Other designs might use FMs at the top level inherently. Suh's [1] decomposition of ROI and Cochran's [2] MSDD are designed using the equation for ROI = ((Sales - Cost) / Investment). They use ROI as the FM for FR 0 and the variables in the equation as the FMs for the top level FRs, even if they don't directly mention metrics. Cochran's [21] CSD is an example of a system that assigns FMs and PMs to the top level FRs and DPs as well as at lower levels where needed.

Suh [22] states that FR = f(DP). The same comparison might be used for FM = f(PM). Suh's [1] faucet design provides independent control of temperature and flow. This design uses FMs and PMs for FRs and DPs 1 and 2 respectively. Flow (Q) = f(Angle of rotation of faucet handle 1) and Temperature (T) = f(Angle of rotation of faucet handle 2), and so the functional relation between FM and PM might hold true. There is no top level FM or PM that is the sum or product of the lower level FMs and PMs, yet it is considered CEME.

It is possible that for systems, like those that use ROI, in which the top level FM trending in one direction or the other is considered positive or negative, a top level metric to monitor the system's overall trend might be important. However in a system like the faucet, the flow increasing or decreasing is not necessarily considered negative or positive, and so a top level FM might not be as important.

Cochran's [21] paper states that PMs are often binary. A binary PM measures whether or not there is a DP implemented to satisfy the FR. A binary PM might not be the best choice of PM for a DP. A non-binary PM would measure how well the DP satisfies the FR, which might be a more valuable measurement. If some PMs can be binary and some are not then the sum of children PMs might not equal the parent.

PMs might be a useful tool to facilitate determining the next level of the decomposition. If a FR was "control deflection in the structure, then the FM might be the amount of deflection. The DP could be "beam" and the PM might be the beam length or the elastic modulus, both of which are dimensions of a beam affecting deflection (Deflection = f(length) and deflection = f(elastic modulus)). This might be an indication that the FR DP pair should be decomposed again to measure each PM.

FMs and PMs might be interchangeable. Labor cost = f(Hours), but hours could be used as a FM just as easily due to the obvious relation between labor cost and labor hours.

Lord Kelvin's quote could be applied to determining CEME in a design. Is it possible to be certain of CEME at any level of a decomposition without a quantitative top level metric as the theme? Using FMs for every FR and decomposing that FM as the theme for the next level of FRs provides a quantitative basis for determining appropriate lower level FRs and maintaining CEME. Without a quantitative justification, claims of a CEME system might be guesses.

4. Conclusions

The current findings indicate that FMs at every level of the design can facilitate designing a quantitatively CEME system. FMs have been used in the third design attempt to decompose a CEME system. Each level of FMs is determined using the FM from the level above. Each child FM controls a variable from the parent FM equation or expression. This can be repeated down to lower level independent variables or until the method for determining those variables is obvious.

The current findings indicate that children FMs should sum to equal the parent, if sum is defined as combine instead of solely as addition. This has been an understood concept in previous works dating back to Suh [1] and Cochran [2], seeing as their top level equation features subtraction and division. However when talking quantitatively, to avoid confusion, it might be more accurate to say that the children combine to equal the parent.

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