A New, Uncertainty-aware Cost-Model for Cost-Benefit Assessment of Robot Systems

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***Abstract*—This paper introduces a new cost-model for robot systems with cognitive features for the use in small and medium sized enterprises (SME). The model combines approaches from activity-based costing and life-cycle costing to reflect machine and production-centric aspects of the use of robot systems. Key contribution of this paper is the handling of uncertainty in the input parameters of the cost-model by using methods from interval analysis. This approach allows to compute explicitly best and worst case scenarios without manual variation of parameters. The cost-model is tested for an application scenario for robotic de-burring and shows the economic performance of the robot system in best and worst case in an intuitive way.**

***Index Terms*—Cost-benefit model, Investment decision, Life-cycle costing, Robot Systems**

I. Introduction

Central questions that arise when designing a robot system to automate a manual task are:

- Is an automation of this task economically feasible?
- How should the robot system be designed for the best trade-off in performance and cost-effectiveness?
- What happens if the made assumptions are wrong or the production mix changes?

To answer these questions a cost-benefit model for the robot system is required. While in mass production scenarios, like car production, with long planning and production cycles, elaborate cost-models and large sets of historical data are available this does not hold for small and medium sized enterprises (SME). However, as robot systems now can be equipped with increasingly elaborate cognitive features such as automatic programming and motion generation based on CAD and sensor data they can be applied for production scenarios with small lot sizes and a high number of variants. As only 22% of small-series production processes are currently automated [1] there is a huge potential for automation in this field. However, for these scenarios the established cost-models cannot be applied and existing data is not available. The main stakeholders on the market for industrial robot systems are component suppliers, system integrators and end-users. This specialization allows the creation of very complex robot systems, but the resulting market fragmentation inhibits the creation of integrated cost-models and data bases as market stakeholders only serve a very limited scope of the market. In particular, the missing data base is a hindrance for the use of total cost-models [2]. Further robot systems for SMEs are typically special machinery and build only once or few times. Therefore, transfer of data between robot installations is difficult as different systems are built by different partners in very small numbers.

This paper introduces a new cost-benefit model targeted at the cost-assessment of robot systems with cognitive features to make a first step towards improved evaluation of cost-effectiveness for robot systems in SME applications. The model builds on approaches from activity-based costing [3], total cost of ownership [4] and life-cycle costing [5], but substantiates these approaches for the use in the design phase and the particular cost-structure of robot systems. The model supports the use of uncertain cost-data to represent uncertainty and risk according to Knight's definition [6]. This key contribution of this paper allows consistent consideration of the effect of estimates and fluctuation margins of the model inputs on the result of the cost-calculation. This approach is much easier to handle than the common scenario-based approaches in which input parameters are modified manually.

This paper is organized as follows. After the introduction in chapter I general considerations about costing for robot systems and the used life-cycle model are discussed in chapter II. The detailed cost-model is introduced in chapter III. Chapter IV presents the methods for handling uncertainty in the cost-model. The implementation of the cost-model is outlined in chapter V. Chapter VI presents results from the use of the cost-model in planning of robot system and chapter VII presents the conclusions and gives an outlook on further research.

II. General Considerations

The model borrows from approaches from life-cycle costing and activity-based costing. Life-cycle costing incorporates a machine-centric view important for robot systems due to their nature as special machinery. Activity-based costing incorporates the production-centric approach and the distribution of costs and benefits to products.

A. Used life-cycle model

The presented cost-model borrows from life-cycle cost-models established in literature [7], [8] and standards [9]. The model used here is shown in figure 1. For robot systems in particular the implementation, reconfiguration and maintenance phases typically cause significant costs since robot systems are special machinery with high engineering efforts and associated development risks. These are often neglected in cost-benefit computations.

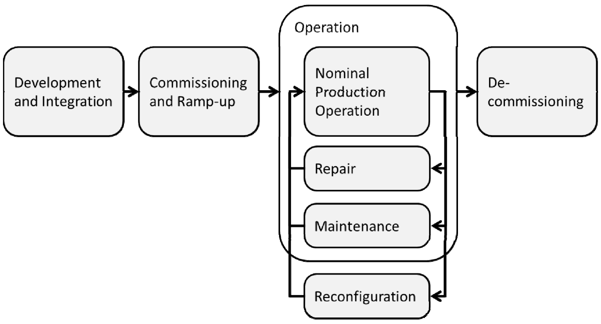

Fig. 1. Used life-cycle model.

During the development phase the robot system is developed and the responsibility is mostly at the system integrator. During commissioning and ramp-up the system is installed at the site of the end-user. In this phase the responsibility for the system shifts gradually from system integrator to end-user. In particular, interruptions of the production and temporary reductions of output have to be taken into account as the robot system is put into operation. This phase and its risks are often underrated by cost-models targeted at standard machinery. During the nominal operation the robot system is operated in normal production. Repair and maintenance operations have to be performed in order to restore or maintain the status of the robot system. However, as these steps are often seen as discrete events occurring during the use of the system and are typically carried out by other stakeholders (system integrator, maintenance department) they are considered separately. During the operation the system might also undergo modifications to adapt it to new products or new product variants. Finally, the decommissioning of the robot system is mentioned for completeness, but typically does not constitute a significant cost-factor.

B. *Machine-centric vs. production-centric approach*

Literature on accounting principles for production processes [3], [10] usually focuses on the production phase in the life-cycle of the production machinery and the assignment of machine cost to the produced product. These publications neglect the design and installation phase of machinery which play a major role for robot systems as they are typically tailor made. Although the cost occurring during the operation phase is typically the biggest portion of cost for flexible robot systems [11] the design and installation phases play an important role as the performance characteristics and occurring cost of capital are defined here. This paper therefore combines approaches from life-cycle costing and activity-based costing to establish a cost-model for robot systems. For this purpose two types of costs, machine-centric costs and production-centric costs, are introduced:

- **Machine-centric cost**: These are costs caused by designing, integrating, owning and maintaining the machine as well as the costs for its components. These costs are independent of actual use and performance of the machine during production. The product of these activities is the machine itself. Therefore, machine-centric costs predominate during the integration phase. In the development and integration phases machine-centric costs are, in addition to engineering costs, strongly driven by purchase of components of the robot system. During the ramp-up phase the focus shifts towards production-centric costs. During the operation the biggest junk of machine-centric costs are activities directed towards maintenance and infrastructure costs.
- **Production-centric cost**: These are costs that are directly driven by the operation of the machine and do not occur if the machine is not actually used in production. They constitute the costs that actually occur by producing products with the machine. For most robot systems production-centric costs dominate during the operation phase.

C. *Activity-based costing*

Activity-based costing is a well researched approach mainly used for the distribution of cost related to production machinery to the products that are produced on this machinery. The scope of this approach is extended here towards machine-driven activities that are carried out to build and maintain the robot system.

The development and integration phase is purely driven by the machine itself, while the nominal operation phase has production-driven aspects, i.e. the cost of carrying out production tasks, and machine-driven aspects, such as cost of capital, space, opportunity and regular maintenance. During commissioning and ramp-up cost are typically machine-driven as the aim of this phase is the establishment of the desired performance of the production machine. The costs of the different life-cycle phases can again be classified by the most basic driver types event, time and activity that govern the occurrence of cost (see table I).

TABLE I
DIFFERENT TYPES OF UNDERLYING DRIVERS FOR COSTS IN ROBOT SYSTEMS

Driver	Description	Example
Event-driven	The cost is triggered by a discrete event.	Replacement of a broken component. Purchase of equipment.
Time-driven	The cost is driven by the time passing while owning the machine	Cost of space and capital. Less production output due to production downtime.
Activity-driven	The cost is driven by a continuous activity that causes a particular amount of cost depending on the intensity of the activity.	Production of a lot. Operation of machine.

Note that the boundaries between the different basic cost-drivers are blurred for some activities and depend on the point of view of the person assessing the cost-effectiveness of the robot system. E.g. maintenance tasks can be viewed as events from the view of the production department, but are rather seen as activities on the side of the maintenance department. However, this classification has been proven useful in practice (see chapter VI).

III. Cost-model

The cost-model borrows from activity-based costing approaches and aligns different activities in the defined life-cycle of the robot system. It distinguishes between activity-driven, event-driven and time-driven costs as introduced in chapter II.

A. Activity-driven costs

The most relevant type of costs during production is activity-driven costs as outlined in the previous section. Cost-activities are always defined by a cost-driver and a cost-structure that describes how this cost-driver creates cost, when the activity is carried out.

Definition 1 (Cost-activity). A cost-activity is an activity performed by the system integrator or end-user of the robot system that is related to the robot system and causes cost.

The cost-driver is the input quantity that is used to measure the level of the cost-activity and therefore drives the cost of the activity.

Definition 2 (Cost-driver). A cost-driver of an activity related to production-centric or machine-centric activities is defined as the factor that causes the cost of this activity.

A typical production-centric cost-driver for automation solutions is the operation time of the robot system, while the engineering hours for development are a typical machine-centric cost-driver. While the cost-driver is the variable that is used to measure the amount of cost-driving activity, the actual level of this activity at a specific time is called a cost-action.

Definition 3 (Cost-action). A cost-action is a specific amount of activity carried out at a specific time. The unit of measure of the activity-level of a cost-action is the cost-driver.

The cost-actions connected to a cost-activity specify the activity-level in a specified time-interval, i.e. the amount of the cost-driver in that time-interval. Note that cost-actions can be connected to multiple cost-activities and an activity can be connected to multiple cost-actions.

Definition 4 (Activity-level). The activity-level specifies the actual amount of a cost-driver during a specified time-interval.

This paper uses a linear model for cost-activities. The costs caused by cost-activities are defined by two constants, the characteristic quantity and the characteristic cost. The characteristic cost is a specific cost that can typically be obtained from accounting, e.g. the cost of labor per hour or the cost of electricity per kWh. The characteristic quantity can be thought of as a transformation between the cost-driver of the activity and the base unit of the characteristic cost and is usually supplied by the system integrator as it reflects specific performance criteria of the robot system. Usually an activity has several subactivities each described by characteristic cost and characteristic quantity.

Note that this cost-model can be extended, if required by introducing arbitrary functions instead of constants for characteristic cost and characteristic quantities in order to reflect non-linear relations between cost-driver and occurring cost. In that way, e.g. consumption dependent power prices can be taken into consideration.

Summing up the cost of a specific cost-activity can be computed as:

$$C_{AC}(t) = CC * CQ * AL(t) \qquad (1)$$

where:

- CC is the characteristic cost of the activity,
- CQ denotes the characteristic quantity and
- $AL(t)$ is the accumulated activity-level of all cost-actions driving the cost-activity in the discretized time-interval t (see chapter V) of the model.

Please also see figure 2 to obtain a better overview of the structure of the cost-model.

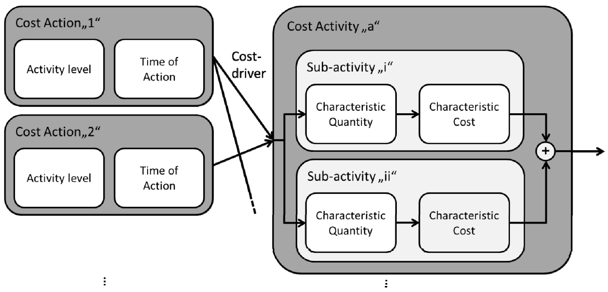

Fig. 2. Structure of the activity-based cost-model.

Event-driven costs and time-driven costs are handled in a similar way.

B. Event-driven costs

For event-driven cost the characteristic quantity refers to the number of units that cause cost for the specific event. The most common event-driven cost-items are purchase of equipment or the complete robot system. Here the characteristic quantity refers to the bill of materials of the purchased equipment. The characteristic cost defines the cost of purchasing one unit. The activity-level for event-driven costs defines the number of events that occurred in a specific time-interval (typically 0 or 1 for robot systems). Therefore the event-driven costs $C_E(t)$ in the discretized time-interval t can be computed as:

$$C_{AC}(t) = \sum_i (CC_i * CQ_i) * AL(t) \qquad (2)$$

The term $\sum_i (CC_i * CQ_i)$ specifies the complete cost of one event by adding the cost of all single components i and their quantities.

C. Time-driven costs

For time-driven cost the characteristic quantity transforms the passed time into the time that the resource is actually used. It is set to 1 in most occasions. The characteristic cost is the cost per time-unit for the time-based cost-item, e.g. the yearly interest for capital cost. The activity-level is always set to 1 while the time of action is usually an extended time-interval that typically spans entire life-cycle phases of the robot system. Therefore, the time-driven costs $C_T(t)$ in a discretized time-interval *t* can be computed as:

$$C_T(t) = CC(t) * CQ(t) * \Delta t \quad (3)$$

where Δt denotes the length of the discretized time-interval (typically 1 day, see chapter V). Note that it is assumed here that characteristic cost and characteristic quantity are constant in the discretized time-interval, which usually holds for the used time-discretization for robot systems. However, if required, fluctuations can be tracked by integrating over the time-interval Δt.

D. Considered costs

Table II lists typical activity-driven, event-driven and time-driven costs for robot systems that are considered in the model.

TABLE II
TYPICAL COST-TYPES FOR ROBOT SYSTEMS
(FROM THE END-USERS PERSPECTIVE)

Cost	Cost-type[1]	Life-cycle Phases[2]	Focus[3]
Equipment cost	EB	DI, RC	MC
Development and engineering	AB	DI, RC	MC
Installation and initial operation	AB	DI	MC
Training	EB	DI	MC
Lost production capacity	EB	CR, O	PC
Consumption of energy and utilities	AB	O	PC
Tool wear	AB	O	PC
Labor cost for operator	AB	O	PC
Labor cost for retooling personnel	AB / EB	O	PC
Maintenance	EB / TB	O	MC
Repair of machine	EB	O	MC
Cost of space	TB	O, RC	PC
Cost of capital	TB	O, RC	MC

IV. HANDLING OF UNCERTAINTIES

As robot systems are typically special machinery not all input data is known during the cost-assessment of the robot system which is usually carried out in the development and integration phase. For example the real-world performance values and the real efforts for installation and production ramp-up cannot be known during the design and investment decision phase before the system has been built. Therefore, assumptions regarding these efforts and costs need to be made. Other sources of uncertainty for the final cost-effectiveness of the robot system are the risks resulting from possible market changes, e.g. leading to changed production volumes. However, typically experts are able to name an interval in which they expect the final values to settle. To assess the sensitivity of the cost-model with respect to uncertainties and risk usually a nominal value is used to compute the cost-model and then the input parameters are varied individually, e.g. through Monte Carlo Methods, to assess the effect of these variations on the results of the cost-model [12]. This approach is cumbersome, as parameters have to be varied manually and the results need to be interpreted individually. The authors of this paper aim for an integrated approach that allows computing the cost-model with uncertainties and risk attached to all input parameters of the model.

To achieve this methods of interval arithmetic [13] are used in the cost-model to handle uncertainty. While traditional cost-models operate on real numbers the developed cost-model operates on “uncertain” numbers x_I that are represented by an interval with lower border or infimum, a, and upper border or supremum, b:

$$x_I = [a,b] = \{x \in \Re \mid a \le x \le b\} \quad (4)$$

As outlined in [14] basic arithmetic operations on interval numbers $x_I = [a,b]$ and $y_I = [c,d]$ are carried out as follows:

- Summation:
  $$x_I + y_I = [a+c, b+d] \quad (5)$$
- Differentiation:
- $$x_I - y_I = [a-d, b-c] \quad (6)$$
- Multiplication:
  $$x_I * y_I = [\min(ac,ad,bc,bd), \max(ac,ad,bc,bd)] \quad (7)$$
- Division:
  $$x_I / y_I = [a,b] * [1/d, 1/c], \text{ if } 0 \notin [c,d] \quad (8)$$

Interval arithmetic guarantees that if the real input values lie inside the specified intervals that also the result is inside of the interval obtained through interval arithmetic. Therefore this approach allows obtaining strict bounds for best and worst case economic performance under the assumption that the expert setting the input intervals has chosen the right interval bounds. A comparable use of the method of interval arithmetic to account for uncertainties and risk in the economic assessment of production machinery is not known to the authors and is the main contribution of this paper.

V. IMPLEMENTATION

The cost-model has been implemented as Windows forms application in C#. To make uncertainty computation available throughout the model a class for uncertain numbers with supercharged operators for basic arithmetic operations has been created. Special classes representing cash-flows, interest rates and activities use this class. This implementation ensures that interval arithmetic is used throughout the entire implementation. All input parameters of the model including interest rates on capital, cash-flows, assumed work effort or basic costs like hourly material cost can be set as uncertain numbers.

The amortization curve of the investment in the robot system is used for visualization of the results of the cost-model. For this purpose the initial investment and its payback due to the production on the machine are plotted along the time-axis (see figure 3). This type of visuali-

[1] AB: Activity-based; EB: Event-based; TB: Time-based
[2] DI: Development and integration; CR: Commissioning and ramp-up; O: Operation; RC: Reconfiguration; DC: Decommissioning
[3] MC: machine-centric; PC: production-centric

zation directly shows the break-even and is intuitively understandable for people familiar with investment decisions.

To obtain the graph the cost-model is computed for a time-interval starting with the first payment t_{ini} by the end-user for the robot system. The time-interval in which the model is computed is then continuously expanded to obtain the amortization curve of the robot system. For numerical computation the time is discretized. As often work task and production schedules for robot systems are planned on daily basis, work days are chosen for discretization of the model. This offers a good compromise between time-resolution and computational effort. The accumulated cost and benefit measure $C(T)$ that occurred up to time T is computed as the sum of the cash-flows that are discounted to t_{ini} with interest rate p:

$$C(T) = \sum_{t=t_{ini}}^{T} \left[\frac{C_{tot}(t)}{1+p^{(t_{ini}-t)}}\right] \quad (9)$$

Here $C_{tot}(t)$ is the cost occurring in time-interval t, which is the sum of activity-driven costs $C_{AC}(t)$, time-driven costs $C_T(t)$ and event-driven costs $C_E(t)$:

$$C_{tot}(t) = \sum [C_{AC}(t) + C_T(t) + C_E(t)] \quad (10)$$

This approach takes the view of an end-user buying the machine from a system integrator where activities carried out by the system integrator are bundled in the payments. However, the cost-model could also be detailed in the design phase if system integration is carried out in-house (see model in chapter VI).

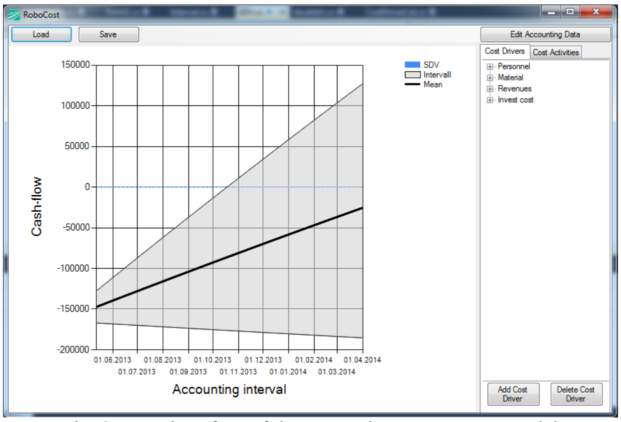

Fig. 3. User-interface of the uncertainty-aware cost-model.

VI. USE OF COST-MODEL

For demonstrating the use of the cost-model and showing the type of information that obtained from the use of the model it has been applied to a robot system in the area of automated deburring of large scale parts. The system features sensor functionality for CAD-based referencing to allow for processing of lot size 1 parts. To use the cost-model with uncertain cost-data the cost-data gathered in the project was used and augmented by experts with uncertainty intervals.

The cost-items shown in table III are included in the model based on customer interviews and expert recommendations.

TABLE III
COST-BENEFIT-ITEMS FOR LARGE SCALE DEBURRING ROBOT SYSTEM

Cost-Activity	Related Cost-actions	Comment
Purchase of robot system	First down payment, acceptance payment	The customer bought integrated hardware from a system integrator with payment in two tranches
Software engineering	Development of various manufacturing software tools for lot size 1 production	Due to in-house capabilities and strategic considerations the customer decided to develop the software for lot size 1 production in-house
Maintenance	Yearly inspections	Assumption of 5% of invest cost with uncertainty of 25%
Electric energy consumption	Machine use, ramp-up	-
Operation personnel cost	Machine use, ramp-up	-
Saving of manual labor cost	Machine use	Due to the use of the automation system efforts for manual deburring are saved
Tool wear	Production of work piece, ramp-up	The automated process requires different, more expensive tools than the manual process. The wear of tools for the automated process appears on the cost-side, while the tool wear for manual tools appears on the benefit side (savings).
Manual tool wear	Production of work piece	

Figure 4 shows the annotated amortization curve from the cost-model for the deburring use-case. It can be seen that the nominal break-even for the system, i.e. the return on investment (ROI) as computed with a traditional, non-uncertainty-aware cost-model is about 4 years. This is well beyond the ROI of 2-3 years usually accepted by end-users for automation systems. However, as for the current customer the system has strategic implications the customer was willing to accept this ROI. But beyond that the model shows how uncertainties in the assumptions influence the uncertainty in the ROI. It can be seen that, as expected, the uncertainty in the predictions of the model increases over time.

The model allows obtaining additional information apart from nominal cost-benefit-data found in existing cost-models. While in the best case the system pays back after about 2.5 years, payback in the worst case takes more than 7 years. The reduced influence of future cash-flows due to the discounting of cash-flows is clearly visible. Note that also the discounting rate in the implemented model is an uncertain number adding to the level of uncertainty in the predictions. When switching on and off uncertainties for single input parameters it is observed that in particular ramp-up efforts and personnel costs for operation and manual labor have significant influence on the profitability of the system. This was expected as ramp-up costs occur at early project phases and often disrupt normal production. Nevertheless, ramp-up costs are often neglected in cost-models. Also personnel costs have a big influence on the profitability as they are for this robot system, like for most automation solutions, the main driver for automation. In the current case the uncertainty-aware model helped enormously to gain an understanding of the risk and different scenarios associated with the automation solution.

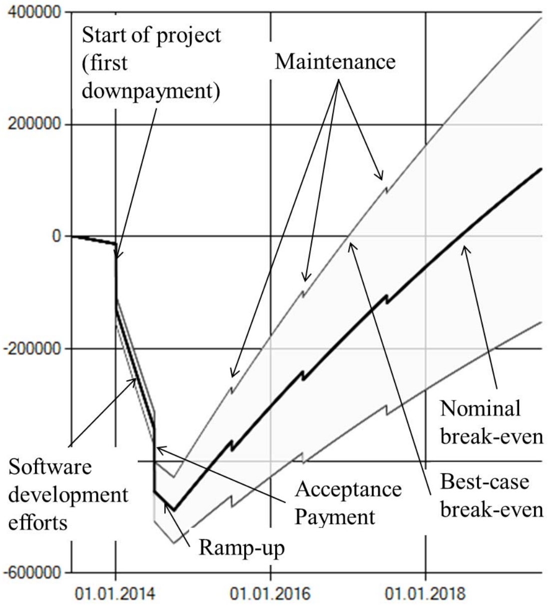

Fig. 4. Amortization curve for deburring use-case.

VII. Conclusions

The new cost-model derived from principles of life-cycle costing and activity-based costing proved useful for the design and cost-assessment of robotic systems. In particular in early design phases of robot systems the model was applied in several projects and increased the comparability of results and fostered to re-use of data between projects through a common model structure. The proposed structure was found to reflect cost and benefit types that typically occur in industrial robot systems. The description of activities as characteristic quantities and cost allows abstraction and transfer of cost-data to similar projects. Furthermore, they reflect the fact that this data is typically supplied by different stakeholders in the company. Currently means are under research for relating these data directly to engineering models of the robot system and accounting models. The uncertainty-awareness of the model allows to immediately assess the effect of uncertainties in the input parameters, e.g. by uncertain performance characteristics of the robot system, on the cost-effectiveness of the final robot system. This approach proved to be a lot more intuitive than scenario-based computations that do not offer an immediate visualization of best and worst case economic performance. The ability to explicitly process uncertainty information with the cost-model was not found in other cost-models for automation systems or capital equipment purchasing known to the authors.

With the uncertainty-aware cost-model the foundation for a new type of cost-model for the economic assessment of robot systems has been created. Future research will elaborate on the used cost-structure of robot systems to make it applicable to more types of industrial robot systems. Further a closer connection to engineering models used in plant design for the automatic determination of the input values of the cost-model is currently under research. Additional descriptions of uncertainties and risks, e.g. normally distributed risks, should be considered in the cost-model and integrated in the developed software. This will also raise the question what description format is most suitable for the description of what type of uncertainty and risk that will be answered by future research. Furthermore research on how data from existing automation projects can be clustered with respect to typical cost-drivers to re-use that data for similar projects is currently under way.

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