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Design for Reuse: residual value monitoring of power electronics' components

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Abstract

Extending electronics' lifespan is a major issue in Design for Sustainability. Power electronic components are a continuously growing part of our daily good service usages from the laptop charger (10–100 W), the home air conditioning (1–10 kW), the solar power plant (1–100 kW), to the railway electric mobility (1–100 MW). They drastically contribute to increasing the e-waste stream since device volume is proportional to power ratings. Repairing conversion systems challenges designers in the way the systems should be designed to be maintained over the years. In addition, introducing circular economy with electronic component (or sub systems) reuse supposes evaluating their residual value in case of power electronics. This paper firstly introduces from the state of the art the residual value evaluations to define the relevant parameters that should be included in the case of power electronic components (e.g.: Mean Time between Failures – MTBF – multifactorial function, rating of components market price, inner residual critical materials, the embodied energy, etc.), and a method to estimate this value is proposed.

Keywords: Design for Reuse, Design for Modularity, Design to Environment, Ecodesign, Power electronics, Lifetime Monitoring, Extended Lifespan, WEEE

1. Introduction

Volume of electronic equipment waste mounts and the supply risks are increasing [1]. Alternative streams for electronic equipment waste should be developed, allowing the devices, sub-systems and components to have multiple lives and usages. A significant benefit could be to take advantage of the remaining value of the device, or even part of it in order to globally minimize the impacts generated on the environment to satisfy functional services.

Power Electronics (PE) represents an important fraction of electronics supporting energy grids as well as everyday home and industrial appliances [2]. Such PE functionalities are requested in nearly all daily life devices from micro to macro scales: small home appliances, the train traction drive, the lighting control, solar panels, etc.

To address these large applications specificities,, numerous and different technologies, as well as converter topologies are considered together with different voltages, current and power ratings. Power converters therefore range from Watts up to Megawatts.

As mentioned, PE converters are used to convert power from its production source to its distribution and consumption. PE differs from casual electronics with the voltage and power ratings of the active components, the transistors and diodes (MOSFET, IGBT, thyristors, power diodes…). However, the most important difference relies on the use and implementation of insulation and energy storage devices required to insulate sources or to filter out the switched voltage and current waveforms. These passive components–capacitor, inductor, transformer (etc.)–physically vary in their proportional dimensions in regard to the amount of energy transfer or the energy to be stored. Together, active and passive components are interconnected with thick copper traces and bus bar. They are cooled down with the help of massive aluminum heatsinks. Overall, power electronics converters remain ‘bulky’, as illustrated Fig.1 below, even if power densities are increasing due to design optimizations and material/ technology improvements The converter functional efficiency is today most of the time quite satisfactory, ranging from 80 up to 99%. As a reference, the power density of PV panel inverters ranges from one to 3 kW/kg. In other words, a 10 kW solar inverter weighs about three to 10 kg [3]. At last, the reliability of power converters is stressed by thermomechanical cycling and their lifespan ranges from 10 to 15 years on average.

Fig. 1. Example of a converter

The large usage of PE based devices is therefore contributing to the ever-increasing e-waste fraction [4]. Rethinking their End-of-Life managementand prior to this, rethinking their reuse is urgent to increase the PE based component lifespan, and then to reduce the negative environmental impacts generated from recovering the high value components, and to avoid constructing additional devices to repair existing one. Supporting such life cycle design strategies faces several obstacles at the micro level of the product (to start with):

- Technical : absence of quality statements for recovered components, or extended lifespan ones (e.g.: repaired);
- Managerial organization value chains: lack of design standardization in components integration, in-operational disassembly chains (not yet) or immature technical and logistic infrastructure organization able to handle such recovered devices revalue (or reintegration) [5];
- Technical-Economic-Environmental issues: a hard balance between technical quality, functional reliability, environmental multi-indicator impact assessment, and costs in a competitive industrialized international world market, not supported by sufficient policy incentives [6].

Those issues are common to most application fields and all power range families but are addressed differently regarding the maturity of the maintenance/repair/remanufacturing scheme already in place [7][8]. PE converters are usually sub systems of a more complex device, and part of a value chain. In renewable energies for instance, the solar inverter is a part of the energy source that also includes PV panels, cables, holders and protections. Similarly, for wind turbines, the electronic and PE parts are subsystems. This electrical part can be critical when it records the highest annual failure rate [9]. Therefore, monitoring the state of health and the residual functional value of the power electronic devices, at the level of granularity that suits for the system considered and in regard to the components reuse potential, appears critical. Such recording method would support maintenance, repair and possibly devices circularity strategies management.

This research aims to contribute to this purpose: to develop, on existing equipments, a higher knowledge and expertise, such as indicators specific to power electronics that would be added to circularity strategies’ indicators developed today to target circular sustainability.

This paper contributes to a better evaluation of PE based systems residual functional value. Section 2 describes a generic residual value function, depending on several parameters, including the Mean Time Between Failure (MTBF). Section 3 proposes a ‘real-time’ MTBF estimation method adapted to the PE-based systems in reuse contexts. Section 4 applies the MTBF multicomponent monitoring, illustrated in Section 5 on a DC/DC power converter, developed for mass production.

This paper concludes on the potential of this method to help designers to evaluate the residual value of PE based components during their lifespan.

2. Residual functional value definition

The life cycle of electrical devices are described in this research through three main steps:

- The first one being the production step: including the raw material extraction, the components manufacturing, the system assembly and the diverse logistics associated.
- Secondly, the use step: including the use time of the device, the maintenance and repair procedures for multiple reuses, as well as the logistics associated.
- Lastly, the End-of-Life step of the device, not necessarily concerning all its components: including collecting, sorting, disassembling and either refurbishing or recycling, burning or landfilling, with associated logistics..

Over its lifetime the converter degrades. Every component age differently at various speeds. Thus within the system, numerous subsystems have different residual values when the whole converter breaks. Detecting the residual value of every subsystem or component is therefore necessary to consider saving them from the waste stream and recycle their usage.

The residual value of an electronic component is the remaining value of this component after a certain time of use in certain conditions. It represents its ability to keep performing its tasks and main characteristics. This value usually decreases with respect to the time of usage as the component ages and its electrical and material properties degrade. However, in case of a supply rarity, it could increase. These statements illustrates that the remaining value must be considered, not only as an absolute indicator, but also as a relative one. Residual value may be assess through the life cycle costing (LLC) method [De Menna, Dietershagen, Loubiere & Vittuari, 2018; Dhillon, 2009; Heralova, 2017]. These models are evolving with the complexity of nowadays products and the different stakeholders taking part in the End-Of-Use of a product[Cooper, 1994, p. 5]. However the functional value should not only based on a cost estimation.

The value of a device is not static as a lifetime warranty. As illustrated in Fig. 2, a number of factors contribute to the rise or drop of the residual value of a component, for instance

- The reuse rate $Rrate$: an empirical value obtained from repairing experiments; this indicates the number of times the components can be successively reused, conferring a high value for the next use phases [11], this rate should integrate the functional value in its inherent complexity.

- The environmental footprint and cost of reuse processes: a theoretical indicator made of a scoring system that groups three other criteria – the number of disassembly tools used, the time spent, and the energy consumed [12] in addition to environmental footprint estimations.

A simplistic residual value model can be expressed through:

$$Vres = Env.FP_{ND}(t).e^{-\frac{t}{MTBF(t)}} \times Rrate - \left[\sum_{reuse\ processes} Env.FP(t)\right] \quad (2)$$

$Env.FPND$ is the environmental footprint of a device at a given location and time context, MTBF is the mean time between failure, in this case it is also the remaining lifetime.

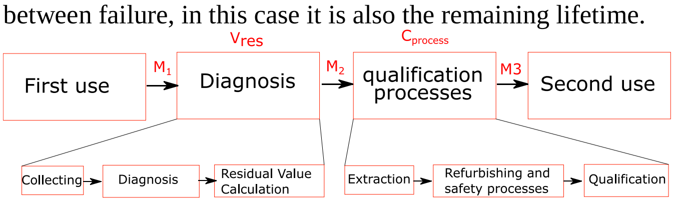

Fig. 2. the steps between the first use and the second life of a component/subsystem

This residual value should be calculated during the diagnosis phase right after the 'last' use and should help manufacturers decide rather the device is worth being refurbished or not.

The residual functional value is not an economic value; it is a decision-support indicator for component state-of-health sorting. The economic value could be calculated out of the residual value by adding the costs of the following processes and the margins taken by the refurbishment actors involved. Existing methods of monitoring the condition of the components for safety reasons are either model-based or sensor-based.

The suggested method in this article is to monitor the residual value by monitoring the remaining lifetime at component and subsystem levels. This is performed with a mix of model-based methods from FIDES failures models and experimental sensor-based methods obtained by IR thermal image capturing. FIDES is a guide to perform predictive reliability calculations for electronic components and systems with empirical models [13]. This complementarity of methods and models should provide an improvement of accuracy in the theoretical models [14], making it possible to tune the functional residual value of any components.

3. Physics of Failure

3.1. Reliability and MTBF definition

The conditions of a component use are required to calculate the residual functional value of this component at a given moment of its life. PE components age faster when they are subjected to higher temperatures, large temperature cycles or mechanical and chemical stresses such as vibration, corrosion or moisture. The cause of ageing can be classified into four families: contamination, humidity, vibration, temperature [15]. Temperature and thermal cycling alone account for about two third of the ageing process. If the temperature profile of each moment of use of the component can be observed or determined precisely, it would help diagnose the state of wear of the component and thus to calculate the approximate remaining life.

PE components are very heterogeneous, in terms of their size, their assembly techniques and their material and chemical constitution. This implies a non-homogeneous ageing of each component of the same electronic board [16]. In this article, the reliability models that link wear parameters to component life are taken from the FIDES manual.

The FIDES reliability guide categorizes electronic components into several families and sub-families such as electrolytic capacitors, integrated circuits or optical devices as optocouplers. For each category of component family, specific models are proposed. FIDES reliability models are generically expressed as in equation (3)

$$\lambda = \left(\sum \begin{matrix} Physical \\ contribution \end{matrix}\right) \times \left(\sum \begin{matrix} Process \\ contribution \end{matrix}\right) \quad (3)$$

- λ is the failure rate of a component
- The left term represents the additive constructions of the physical and technological failure contributions to reliability
- The right term represents the sum of the impacts of the development, production, and operation processes on reliability.

The physical contribution to the reliability is expressed in (4) as mentioned in FIDES:

$$\lambda_{Physical} = \left[\sum_{\substack{Physical \\ Contribution}} \lambda_0 \cdot \pi_{acceleration}\right] \times \pi_{induced} \quad (4)$$

- The term in square brackets represents the contribution of physical stresses on the failure acceleration, $\lambda 0$ is a constant parameter for every component and it represents the reliability in a perfect environment
- π_induced represents the contribution of induced factors (also called accidental overload or over stresses) inherent to an application domain.

The acceleration factor π is declined for each physical constraint applied to a component during its operational use, including the following design parameters:

- Thermal: the integrated circuit technology, the junction temperature of the component, the ambient temperature, the thermal cycling level, the casing.
- Electrical: current ripples, nominal voltages, power;
- Mechanical: vibrations endured, collisions endorsed, solder paste type, number of pins, heatsink and casing materials.
- Chemical: presence of pollutants, fine particles rate.
- Humidity: variation profile during use.

The MTBF is the mean time between failure and it is also expressed as the time in millions of hours when 63% of a sample of the same component fails. It is therefore a probabilistic approach to the moment component may fail. So, it can be used as an indicator of the remaining life of a given component. The MTBF is the inverse of the failure rate and its unit is in hours given by (5):

$$MTBF = \frac{1}{\lambda} \quad (5)$$

3.2. FIDES reliability model improvement

FIDES models are a basis for mean reliability calculation but they are not sufficient to estimate the residual value of a component. They must be coupled with a precise knowledge of the component life condition during its whole life. The sensitivity of FIDES reliability models to wear parameters is exemplified below, in the case of a family of magnetic components: low current wound inductors, an essential and specific component category in PE.

$$\Pi Thermal = 0.01 \times e^{11604 \times 0.15 \times \left[\frac{1}{293} - \frac{1}{(T_a + \Delta T + 273)}\right]} \quad (6)$$

$$\Pi Cycling = 0.73 \times \left(\frac{12 \times N_{cy}}{t_{year}}\right) \times \left(\frac{\min(\theta_{cy}, 2)}{2}\right)^{1/3} \times \left(\frac{\Delta T}{20}\right)^{1,9} \times e^{1414 \times \left[\frac{1}{313} - \frac{1}{(T_{peak} + 273)}\right]} \quad (7)$$

The equation above is the thermal and thermal cycling contributions ($\Pi Thermal, \Pi Cycling$) to ageing in the FIDES reliability models for magnetic components. These models appear dependent to the wear parameters : T_a the ambient temperature, ΔT the temperature rises and Ncythe number of cycles per day. This is illustrated in Fig. 4 where, doubling the amount of thermal cycling triples the acceleration of ageing. Besides, if this cycling is done at high ambient temperature, the ageing accelerates by a factor 4

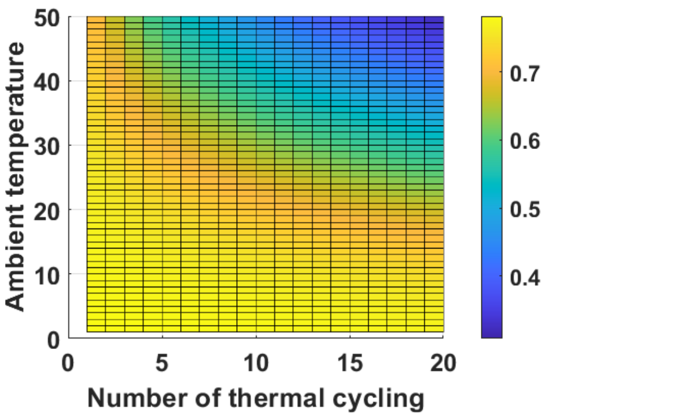

Fig 4. Color map of the theoretical MTBF of a wound inductor versus the ambient temperature and the number of thermal cycles.

Finally, taking into consideration the specific phases of a mission profile (each thermal cycling – duration and magnitude –, different ambient temperatures, etc.) instead of simply taking an average power operation over the year drastically changes the MTBF results [14] by 5% to 30%. Integrating sensors and real-time observers to follow precisely the temperature mission profile of each component to fed FIDES models could help in the residual value estimate.

Thus, the MTBF is improved by a weighted sum of the component's hourly thermal stress related to wear condition by a time factor Δt to obtain the remaining lifetime (RLT (t)) for a given life condition.

$$RLT(t) = MTBF(t) - t \quad (8)$$

Δt is the time the converter spent functioning at a given operating point. t is the total operating time.

In this sectionthe main failure causes have been described. The estimating method for the characterization of the MTBF of components up to devices has been recalled. Mission profile appeared to be an important ageing parameter. And among them, the impact of the temperature profile over usage was underlined. Provide an indicator for each component and subsystem of the power electronic device, therefore requires to develop a set of knowledge on all the components under usage with appropriate sensors or other tools.

The option to implement sensors on each valuable device is not realistic in many cases. Therefore, a limited amount of extra sensor devices must be used in order to determine the desired indicators, ideally from the existing sensors. Our approach is based on prior usage data collection and data learning. We are studying and characterizing at converter level the temperature profile of each component and subsystem with respect to operating conditions and implementation. From this characterization we are then able to supply the MTBF models and then to supply our indicator with an accurate and representative data. Our objectives are to rely only on existing sensors already implemented for the converter operation (control and protections). Acquiring the evolution of the mission profile over time together with observer models from data learning gives the opportunity to determine, in real time the remaining value (need of repair) of each component of a power converter. The following section describes a specific application case on a standard DC/DC converter to illustrate the method.

4. Multicomponent MTBF monitoring

As stated in part two, this work studies FIDES statistical models fed with experimental data to predict the estimated remaining life of a converter with respect to a wide range of operating conditions. It can be divided into 3 parts:

Metrology: the first objective of this work is collecting various IR (Infrared) images at different converter operating points to set a representative database linking the temperature rise of every component of the Printed electronic board with the converter operating point. In Fig. 5 as an example, are given a set of IR images of the lab's DC/DC DAB (see Fig. 7) converter (20 V, 2.5A) in different operating conditions, also recorded at the same time.

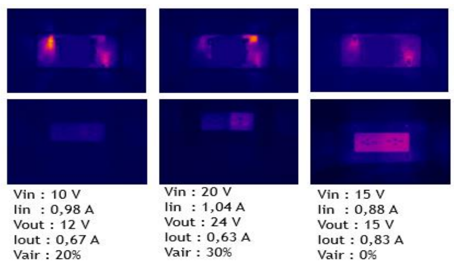

Fig 5. IR images from Fluke camera of a DC/DC converter operating in different operating points, Ta=23°C

Modelling: from IR images analysis, the temperature rise of each component can be related to the converter operating

points. A thermal behavioral model can be built for each component. As introduced above, a second stage modelling fed by the thermal model enables the remaining lifetime derivation from a well-known thermal mission profile.
Fig. 6 summarizes the steps one and two that must be carried out prior converter usage. The collected database is plugged in a machine-learning predictive model that will try to fit statistical tendencies between the operating points and the MTBF. The predictive model is computed in MATLAB with the regression toolbox, and a simple fit can be obtained, we chose a linear regression as it gave satisfactory fitting with 90% explained points on a training database and 83% explained points on the test database.
The operating point parameters are the input and output voltages and currents of the converter $(Vin, Vout, Iin, Iout)$, the ambient temperature Ta and the speed of the forced air $Vair$ In case of active cooling.

$$mtbf(t) = f(V_{in}(t), V_{out}(t), I_{in}(t), I_{out}(t), T_a(t), V_{air}(t)) + \varepsilon i \quad (9)$$

$$\varepsilon i \text{ is the residual error}$$

The hourly thermal stress is the incremental t step to calculate the updated MTBF at time t with the equation 8.
Real time prediction: The model described in the previous stages can be loaded onto the power converter CPU to follow in real time the ageing of each component. In order to implement it, the stress is updated this way in equation 10:

$$Stress_k(t) = \frac{t - \Delta t_k}{t} \times Stressk - 1(t) + \frac{\Delta t_k}{t} \times Stress(t) - t \ (10)$$

With t being the whole operating time, Δtk the duration of a single operating point. k is the operating point change step. This approach is offering the opportunity to integrate aging over time without saving all operating points.
From the former MTBF calculation, a new MTBF at a given time t and operating point change k can be calculated.

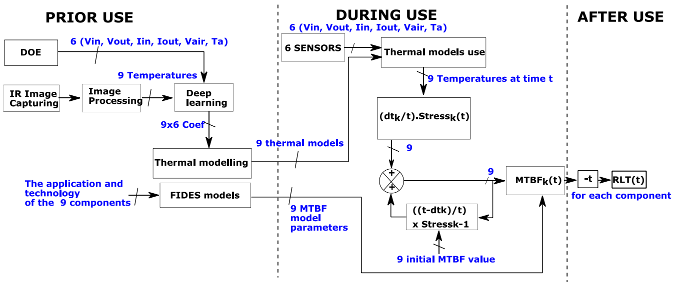

Fig 6. The process of data collection and calculation to obtain the MTBF from the operating points.

5. Practical illustration

In the lab, the MTBF monitoring was performed on the lab's homemade DC/DC DAB converter designed for mass production and illustrated in Fig. 7 [17][18]. The bill of material of this converter is given in Table I hereafter. Table 1. Bill Of Material

Component	Number	Position on PCB
MOSFET	8	Back side
Inductance	1	Front side
Planar transformer	1	Front side
Optocouplers	2	Front side
Drivers	4	Back side
Regulators	2	Front side

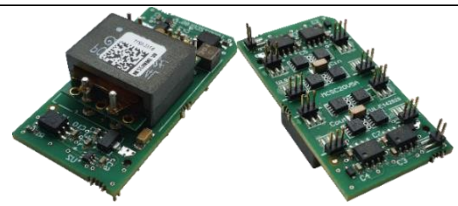

Fig 7. G2Elab DC/DC DAB converter, on the left the front side, on the right of the backside.

To create statistical models that predict with acceptable confidence the output variable (component's temperature), a DOE was set and 130 operating points were examined.

Table 2. Defined variables for the operating point.

Operating point				
Vin [V]	**Vout-Vin[V]**	**Iout [A]**	**Vair [m/s]**	**Ta[°C]**
[10-20]	[-6-6]	[0.75,1.5,2,3.5]	[2,4,8]	[23,40]

The data collection (image capturing) was performed in a controlled environment. For this purpose, the converter was isolated electrically and thermally and was painted black to avoid light reflection on the IR camera and any uncontrolled variables to interfere with the operation of the converter. From the 130 IR images, the steady state temperature of every component was extracted with image processing algorithms on MATLAB. The deep learning algorithm was then trained and tested on the database to create a linear regression for each component temperature with respect to converter operating point. From this, the incremental stress was derived as illustrated equation (11).

Table 3. Performance of the MTBF fitting

Input variables	Target Variable	Fitting	Errors $R2$
Operating point	MTBF (for every component)	Linear regression	83%

$$stress(t) = cst + \alpha.Vin(t) + \beta.Vout(t) + \gamma.Iin(t) + \delta.Iout(t) + \theta.Ta(t) + \rho.Vair(t) + \varepsilon i \quad (11)$$

We have chosen for this application the mission profile in Fig. 8, the ambient temperature is 23 °C and the cooling condition is natural air convection.

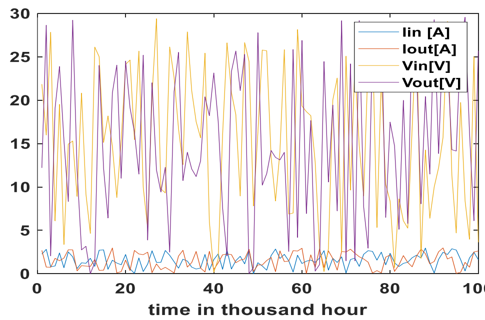

Fig 8. Operating point variables changing

The MTBF for each operating point and component is then obtained and calculated real time applying equation (8) with the microprocessor controlling the converter.

For themission profile in Fig. 8 performed by the converter, the component (inductance) ages like shown in Fig. 9. The remaining lifetime is expressed in percentages as the reliability.

$$Reliability = e^{\frac{-t}{(t)}} \quad (12)$$

As expected, for this given mission profiles, the inductance seems to be ageing in a faster manner in contrary to if one takes an average mission profile or an average operating point over the years. Fig. 9 compares the reliability with a monitored MTBF and the reliability of the average MTBF for the inductance. Note that for [Vin=20V, Vout=20V, Iin=2.5 A, Iout=2A, Ta=23°C and Vair=2m/s], $MTBFMEAN = 95000\, hours$ and the reliability equation for the mean operating point is expressed as given equation (13):

$$Reliability = e^{\frac{-t}{95000}} \quad (13)$$

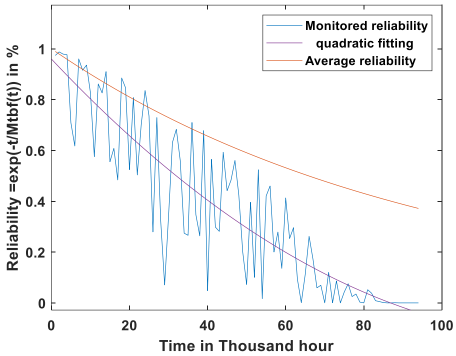

Fig 9. The reliability monitored for the inductance vs the average mission profile reliability

6. Conclusion

To conclude, the residual value has been defined in part 2, stating some of its key assessment parameters. The residual value proposed is not to interpret as a monetary value but rather as an inherent footprint value that can potentially help estimate a residual cost. An important parameter influencing the residual value estimation is the remaining lifetime. A technical functionally based remaining lifetime prediction algorithm has been proposed in part 4 and illustrated in part 5. This case study was carried out with the aim to determine the residual value of a component toward its reuse, even after its embodied equipment has failed. Only a real-time monitoring of its functional life allows to estimate the potential remaining life. This estimation is a basis to guarantee a normal functioning of this component in a similar system reusage.

To reintroduce these components in other similar converters or sell them in an existing second-hand component market, the converters have to be standardized, in regard to its BOM and to the disassembly/assembly processes engaged. Perspective of this work include improving the residual value model proposition by considering the impact of repair processes in remaining lifetime estimation. Because we believe that in addition to inducing mechatronic malfunctions, disassembly, extraction, logistic processes induce an ageing acceleration over time.

A deep understanding of the processes stated in Fig 2, associated to an estimate of their economic cost and environmental footprint will contribute to improve the functional residual value assessment of the component resulting from a defective system in the context of the whole value chain involved.

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