A Cost Analysis of RDL-first and Mold-first Fan-out Wafer Level Packaging

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***Abstract*—Industry interest in fan-out wafer level packaging has been increasing steadily. This is partially because of the potential behind panel-based fan-out packaging, and partially because wafer level packaging may be fulfilling needs not met by interposer-based and 3D technologies. As is the case with any technology, there are variations within the fan-out wafer level packaging category. This paper will focus on two of the primary processes: RDL-first and mold-first (also called chip-first).**

While these process flows have many of the same activities, those activities are carried out in a different order, and there are a few key steps that will differ. Each process has unique challenges and benefits, and these will be explored and analyzed.

Keywords—fan-out; wafer level packaging; WLP; RDL-first; mold-first; cost analysis

I. Introduction

Wafer level packaging (WLP) is already established in the industry in some forms. However, the past two years have seen a distinct growth in interest. The increased interest of the industry may partially be because 3D and interposer-based packaging technologies have not met all of the initial expectations. There is also potential for cost advantages associated with panel-based fan-out packaging. Due to this level of interest in WLP, it is important to understand the different process flows and the major cost and yield drivers. With that understanding, better design decisions can be made.

WLP is generally broken into two categories: fan-in and fan-out. This analysis will focus on fan-out WLP (FOWLP) because there are many configurations and process flows emerging in that category.

II. Mold-first and RDL-first

A. Mold-first

Mold-first (also called chip-first or die-first) FOWLP was previously considered the standard FOWLP process. Infineon introduced eWLB (embedded wafer level ball grid array) in 2007 [1]. eWLB is not the only mold-first process available. Freescale has RCP (redistributed chip package), ASE has aWLP, and TSMC has InFO, to name only a few [2].

Fig. 1 shows the process flow for a generic mold-first FOWLP process. As a generic process flow, it is meant to capture the high-level steps of a typical mold-first process without specifically listing any elements of a proprietary mold-first technology. Different types of mold-first FOWLP will have variations within the process flow.

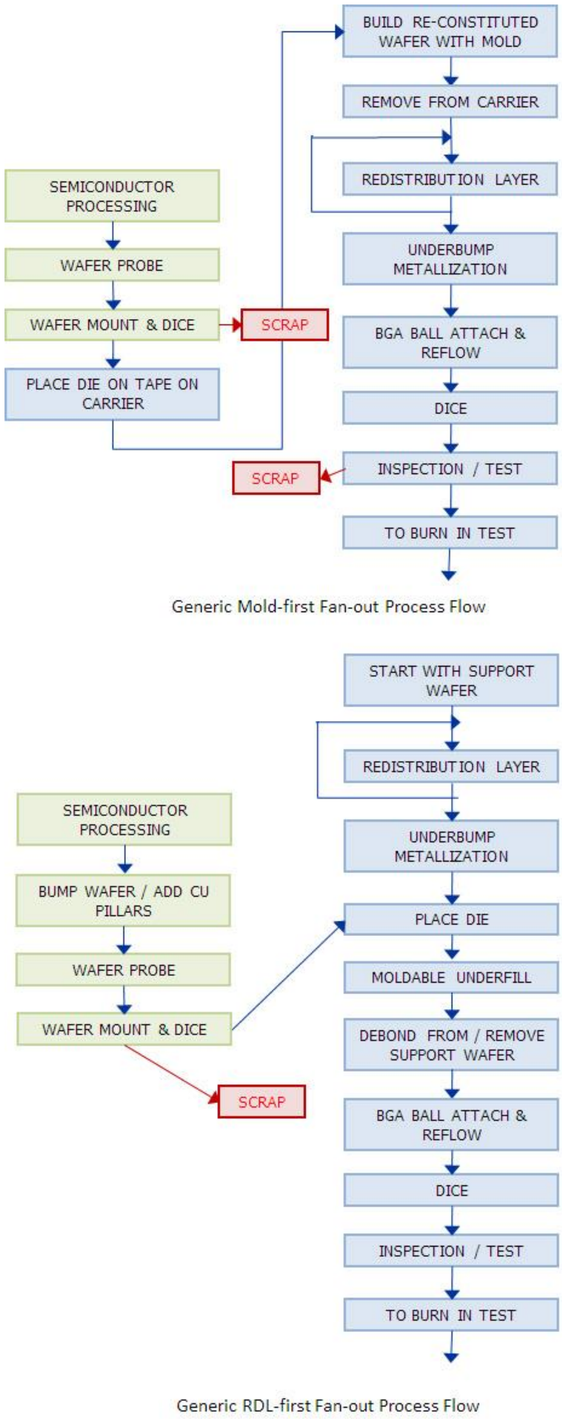

Figure 1. Generic Process Flows

B. *RDL-first*

RDL-first (also called chip-last or die-last) FOWLP is newer to the market. In fact, it would be more correct to call RDL-first an advanced flip chip technology, not a wafer level packaging technology, because of the order of steps in the process flow [2]. As with mold-first, there are many flavors of RDL-first process flows. Renesas, Amkor, and other companies have introduced RDL-first technologies.

Fig. 1 also shows a generic RDL-first process flow. As is the case with the mold-first process, this diagram is meant to display a general RDL-first process with the understanding that variations within the process flow will occur depending on which RDL-first technology is used.

C. *Process Flow Differences*

In this section, some of the key differences between mold-first and RDL-first will be discussed.

When comparing the two process flows, it is immediately apparent that many of the same steps are required for both. The difference is the order in which particular steps occur. Additionally, there are a few activities that are unique to each process flow. This section highlights and explains the key differences.

- Line/Spacing (l/s) requirements – This is not reflected in the process flow diagrams as it is not a step, but it is a key point. The decision between mold-first and RDL-first will not be based solely on the cost of the packaging technology. Mold-first processes are currently in HVM around 10um l/s, with future advances anticipated. RDL-first flows are expected to range from 5um to 2um l/s capabilities [3]. The exact l/s capabilities of mold-first and RDL-first will depend on the design being packaged, and the state of both packaging technologies when the decision is being made. It is important to keep in mind that, regardless of cost, l/s requirements may be a deciding factor when choosing between these two packaging technologies.

- RDL creation – These steps, consisting of two dielectric layers with a metal layer in-between, occur at different points in the flows. However, although RDL creation must occur for both technologies, the actual process used for RDL creation may be different. For example, an RDL may be created on a bump line or at a fab with a damascene process.

- Support wafer – Both processes require some form of carrier. In mold-first, an adhesive foil is laminated on a reusable carrier, and the die are placed on the foil before molding. This is a straightforward process, as is delamination after the die are placed and molded. On the other hand, the carrier required for the RDL-first process is different and variable. Some have suggested using a sacrificial silicon wafer. Others promote the idea of a reusable glass carrier with a sacrificial adhesive layer. In either case, this means the carrier step at the beginning and the debond step midway through the flow have characteristics that are different from the mold-first process.

- Incoming die – The die coming into an RDL-first process must come in with bumps or copper pillars. This is not true for mold-first.

- Mold – Both processes require mold, but the mold compound required to act as a reconstituted wafer prior to RDL processing in a mold-first flow is different from the mold compound that can be used in the RDL-first process.

- Yield – This is a key element to consider for both process flows. The same steps in both flows may introduce the same yield challenges, but these may have a different impact on total cost because it depends on where the step occurs in the flow. Furthermore, some steps may introduce more or less of a yield hit depending on the details of the particular process.

Some of the key concerns related to mold-first FOWLP are surface planarity between the mold and the die, die shift after mold resulting in RDL misalignment, and wafer warpage. Some of the key concerns related to the RDL-first processes are void-free die assembly and issues related to the sacrificial layer or wafer [4].

III. Activity Based Cost Modeling

Activity based cost modeling was used to construct both cost models used in this analysis. With activity based cost modeling, a process flow is divided into a series of activities, and the total cost of each activity is calculated. The cost of each activity is determined by analyzing the following attributes: time required, amount of labor required, cost of material required (consumable and permanent), tooling cost, all capital costs, and yield loss associated with the activity. When this paper refers to process step assumptions, it is referring to these attributes: the throughput of the step, the cost of the equipment, etc.

The graph in Fig. 2 shows an example of the type of output that can be obtained from activity based cost modeling. These are the first few steps of the generic mold-first process flow. The X-axis shows the name of the step; the Y-axis shows the type of cost that is contributing to each step.

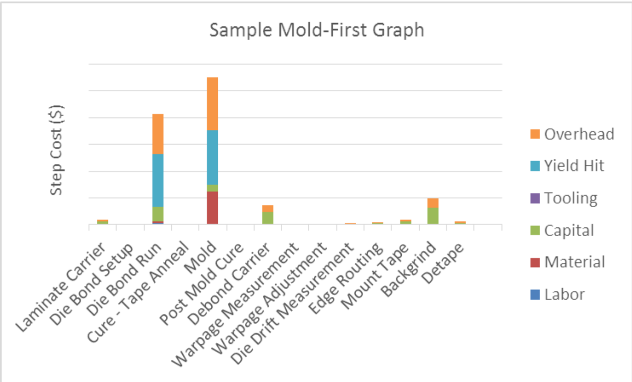

Figure 2. Example of Activity Based Cost Modeling Output

IV. Cost Comparisons

A variety of cost comparisons are included in this section. It is important to remember that the decision regarding which packaging technology is most suitable for a design does not depend only on cost. One key item not included in these direct cost comparisons is any discrepancy between l/s capabilities and requirements. All examples in this paper assume that either of these two packaging technologies will meet product requirements.

The goal of creating generic cost models of mold-first and RDL-first process flows is to understand general design characteristics that impact cost. The results will be useful for suppliers of both technologies: an understanding of the key cost drivers of a generic process can be applied directly to a proprietary process. On the other hand, it is important to note that to fully understand the cost of any version of mold-first or RDL-first technology, a detailed process flow of that particular flow must be constructed. The results of this analysis should be considered guidelines related to cost drivers. These are not conclusions about which packaging technology will always be the most cost-effective.

The basic process flows were introduced in Section II, and major differences have already been highlighted. The cost models are based on the process flows and order of steps shown in Fig. 1. Table 1 captures process step assumptions that are different in the RDL-first flow as compared to mold-first. If a process step is not listed in the table, it can be assumed that the step has the same assumptions in both flows.

TABLE I. Differences in Activity Assumptions

Activity	Adjustment for RDL-First
Incoming die	Die must have bumps or Cu pillars in RDL-first processing → Higher incoming material cost
Die placement throughput	Throughput assumed to be slightly faster than mold-first die placement
Mold	Molded underfill (MUF) assumed to have a lower cost per gram than the mold compound used for mold-first
Carrier/ Support wafer	Carrier for an RDL-first process is assumed to have greater material and processing costs than the foil lamination required in mold-first
Debond	Removal of the carrier is assumed to require more processing than the simple delamination process in mold-firstlarge

To simplify this comparison, no activity yields were adjusted. In other words, when the model assumes a particular number of defects are introduced during RDL creation in mold-first, the same number of defects are assumed to be introduced during RDL creation in RDL-first. However, yield will nevertheless have a different impact on total cost because it depends on when the die is placed. If an expensive die is placed first in the mold-first flow, molded, and there is yield fall out due to RDL processing, some of those die are scrapped. On the other hand, die can be placed in known good locations after RDL creation in the RDL-first process.

As seen in the table, a limited number of assumption changes have been made. SavanSys consultants consider this a conservative approach. Cost models of specific mold-first and RDL-first technologies may require many other process flow adjustments.

A. *Single Die Example*

The first comparison uses a single die design. Three separate sets of analyses were run for this comparison, using three different die sizes. The design characteristics for all cost comparisons, including these single die examples, are listed in Table II.

TABLE II. Designs for Cost Comparisons

# of Die	Package Size (mm)	Die Size (mm)	# of I/Os	# of RDLs
1	10x10	7x7	500	1
1	8x8	5x5	200	1
1	5x5	4x4	120	1
2	15x15	5x5	1000	2
3	20x20	5x5	2000	2

All three 1-die designs were analyzed with the mold-first and RDL-first generic models. In the first set of data, it was assumed that the incoming die to be packaged were from a fairly expensive, advanced node wafer costing $5000 per wafer. The cost of bumping this wafer was added to the incoming die cost in the RDL-first scenarios. In all three cases, the mold-first process flow was more cost-effective than RDL-first.

All three comparisons were re-run with less expensive die, coming from an incoming wafer costing $3000. Mold-first remained the most cost-effective choice in all cases.

The chart in Fig. 3 shows how a 1-die example breaks down when looking at subsections of each process flow.

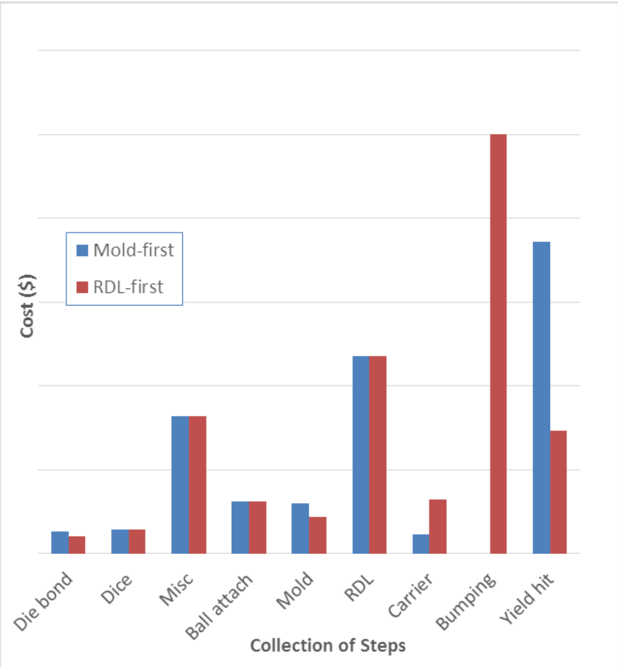

Figure 3. Cost Contributions by Process Flow Section, 1-Die Example

On a summary level, the RDL-first process introduces extra processing and material costs that may be worth it if the yield benefit of placing incoming die in known good locations outweighs those extra costs. In all 1-die examples, the yield of the mold-first process is high enough that the extra costs associated with RDL-first are not cancelled out by scrap cost savings.

B. 2-Die Example

This comparison looks at a larger package with two die and two RDLs. Similar to the 1-die example, both designs were tested when dealing with an expensive $5000 incoming wafer and a less expensive $3000 wafer.

When running the designs with the conservative, baseline assumptions, RDL-first appears to be the cost-effective choice. In large part, this is due to the impact of yield. The RDL creation process carries a yield hit, and since there are two RDLs, the yield impact is compounded. The cost associated with the die that have to be scrapped in the mold-first example is not insignificant—$0.525 is the scrap cost for the entire process ($3000 wafer example). In contrast, the scrap cost for the RDL-first process is $0.255. Even though the material cost associated with the RDL-first process is higher than the material costs of the mold-first process, RDL-first is more cost-effective.

On the other hand, with some additional adjustment to the baseline assumptions for the RDL-first process flow, there are cases in which mold-first becomes cost-effective for this 2-die design. In the case of utilizing less expensive die (from a $3000 wafer), the RDL-first package is less expensive by less than $0.20. This is based on the assumption that the RDL creation process is exactly the same for both mold-first and RDL-first. If, however, the RDL-first process required RDL creation that came with a higher cost, such as by using a damascene process, that alone could cancel out the cost savings and result in mold-first becoming more cost-effective for this two-die design.

C. 3-Die Example

This comparison looks at a complicated, large package with three die and two RDLs. The designs were tested with both an incoming $5000 and $3000 wafer as in the other comparisons.

Unsurprisingly, the RDL-first process is considerably more cost-effective than the mold-first process. This is for the same reasons stated in the 2-die example: a compounding yield problem. A comparison of the cost of different process flow sections is shown in Fig. 4. It looks similar to the chart from Fig. 3, because from a processing perspective, the same steps that were more expensive in a 1-die comparison are still more expensive in a 3-die comparison. However, the difference in the magnitude of yield impact is clearly visible when comparing the two charts.

It is worthwhile to answer the simple question of “which process flow is cheaper for this design” as has been accomplished in this section, but without looking at detailed results, designers and technology suppliers can’t apply these cost comparison results to their specific processes. The next section moves beyond the simple set of baseline assumptions analyzed above and explores more detail through sensitivity analysis.

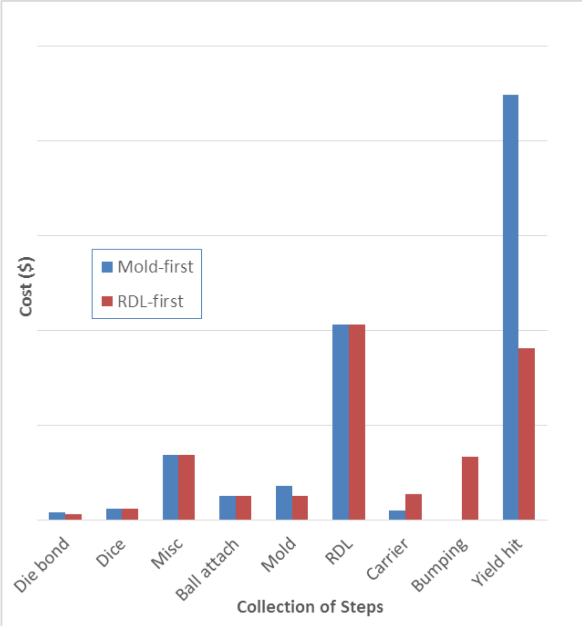

Figure 4. Cost Contributions by Process Flow Section, 3-Die Example

V. Sensitivitiy Analysis

The goal of sensitivity analysis is to see how much of an impact a particular variable has on total cost. Any variable in these process flows could be tested for sensitivity; four were selected as key design and process parameters for these process flows. New designs, different from those in Table II, were created for sensitivity analysis.

A. Support Wafer

Fig. 5 shows the impact of changing the material cost associated with a support wafer in the RDL-first process. This is for a 2-die package.

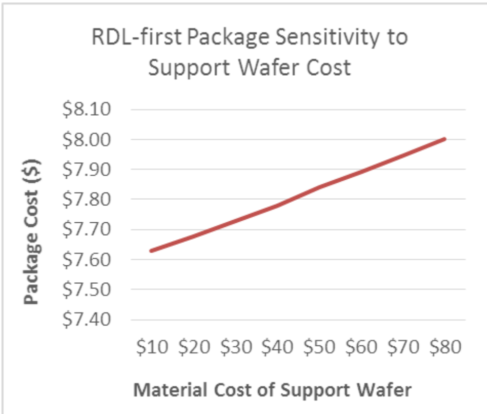

Figure 5. Impact of Support Wafer Material Cost

The low material cost range of the X-axis represents a process such as a fairly inexpensive adhesive spun-on to a reusable glass carrier. The RDL is then built on that spun-on material and the debond step occurs later. The high material cost range represents the impact of using a sacrificial silicon wafer. Using such an expensive support wafer would clearly have an impact on total package cost.

B. *RDL Creation*

The impact of RDL creation cost on the total package cost is important to consider. An RDL-first design was used for this sensitivity analysis because there are variations on what method may be used to form the RDL in this case. There may be changes to mold-first RDL creation in the future as well if process adjustments are made to achieve finer l/s, but for now, the RDL process in current mold-first technology is well-understood. In the case of RDL-first processing, depending on factors like the wafer carrier solution selected and the physical location of RDL-creation (i.e. on a bump line or at a fab), it can't be assumed that RDL creation in an RDL-first process carries the exact same cost as in a mold-first process.

The graph in Fig. 6 starts with a baseline assumption of RDL creation in RDL-first equaling the cost of mold-first RDL processing. That is the 0% point on the X-axis. The package cost was evaluated as RDL creation cost increased by different percentages. It is not out of the realm of possibility that a damascene process may have a 50% cost increase over a bump line process [5].

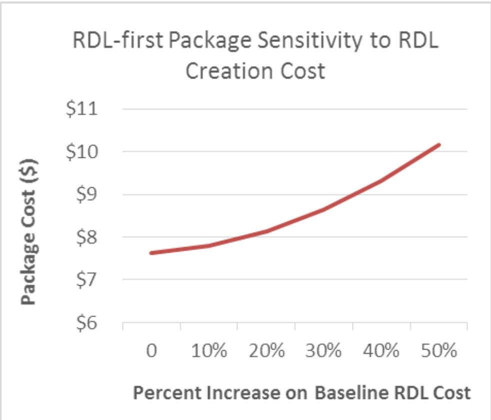

Figure 6. Impact of RDL Creation Cost

This example used a 3-die design.

C. *Die Placement Throughput*

The graph in Fig. 7 explores the impact of die placement throughput on total package cost. A 1-die design was used for this analysis. The factors that would affect throughput are alignment accuracy requirements and the details of the process flow (such as whether or not adaptive patterning is being used later in the flow). Note the scale on the graph: it is very zoomed in. A change of 1000 chips per hour has about a 2 cent impact on total process cost. Based on this analysis, throughput is not a key cost driver of either the mold-first or RDL-first process flows.

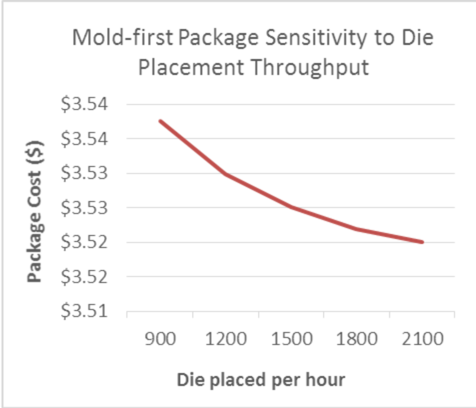

Figure 7. Impact of Die Placement Throughput

D. *Yield*

The impact of yield has been discussed at a higher level already. The key takeaway related to yield is that even if the process flows have the same yield considerations overall and defects are introduced to the same extent in the same steps, there is still a cost impact because the die are placed at different times. That results in a different scrap cost.

It is important to dive deeper into this variable and understand how much of an impact yield may have. A design with two die and two RDLs was evaluated by both the mold-first and RDL-first cost models.

Fig. 8 shows how the cost of this particular design in a mold-first package changes as fewer defects are introduced. A change from 90% to about 96% total process yield results in half a dollar of savings per package. This reveals that yield a key cost driver. Any actions that can be taken to introduce fewer defects in the mold-first process will likely be worthwhile from a total cost perspective.

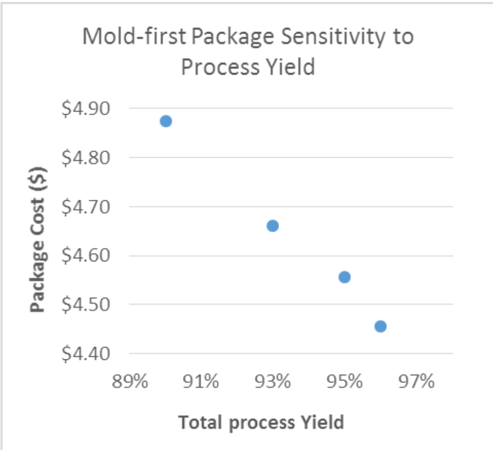

Figure 8. Impact of Yield on Mold-first Process

The impact of changing yield was tested in an RDL-first as well. A two-die design was evaluated in this case as well, but a more expensive die was assumed. Therefore, Fig. 9 cannot be compared directly to the graph in Fig. 8. However, both graphs have a range of approximately fifty cents shown on the Y-axis. This creates a similar scale for both charts and shows more clearly how the processes are impacted to a different extent.

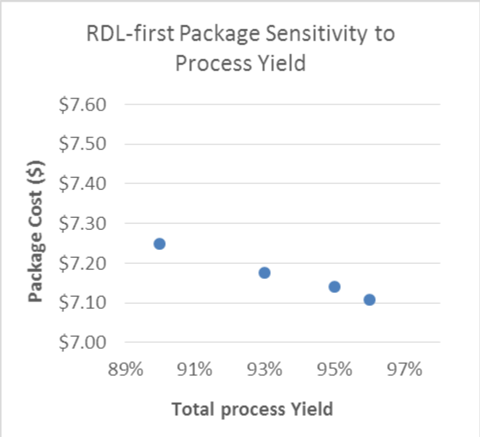

Figure 9. Impact of Process Yield on RDL-first Process

VI. CONCLUSIONS

Generic mold-first and RDL-first process flows were created and analyzed with activity based cost modeling. Key differences between the two technologies were discussed.

Cost comparisons were carried out on multiple designs to determine which packaging technology was more cost-effective in particular scenarios. The cost impact of specific variables was analyzed on a more detailed level through sensitivity analysis.

At a summary level, mold-first technology appeared to be more cost-effective in simpler scenarios, such as when dealing with one die. RDL-first appeared to be more cost-effective in complicated, multi-die and multiple RDL scenarios.

The true conclusion of this analysis is that both mold-first and RDL-fist technologies may be cost-effective in different situations. Any cost trade-off comparing these flows are not simple, because at least one type of cost will generally increase while another decreases (e.g. material cost increases, scrap cost decreases). Quantitative analysis is therefore required each time a designer must determine which packaging technology to use.

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