ROLL-TO-ROLL MANUFACTURING
PROCESS ELEMENTS AND RECENT ADVANCES

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Roll-to-Roll Manufacturing
For Helena, Maya, Eli, Karen, Emre, and Gulgun
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Preface

Roll-to-roll (R2R) manufacturing is a well-established manufacturing technology platform used for over a century in many mature industries, such as printing, paper consumables and silver-halide photography, to produce two-dimensional, film-like products on a mass scale. The main appeal of this technology and the reason for its widespread use is its high throughput capability combined with a low manufacturing cost. The last two decades have seen a strong resurgence of this technology as it is being extended and adapted in many new technology areas, including microelectronics, display and photovoltaics, in an attempt to leverage some of the tangible benefits of R2R manufacturing, especially its low cost, in a new lineup of innovative products.

This volume mainly aims to review the state-of-the-art and shed a new light on R2R technology, to familiarize a new generation of researchers and practitioners with many aspects of this technology as it is being applied in an ever-growing number of industries and product categories. Some key elements of R2R manufacturing are reviewed by highly experienced experts in the field, with emphasis on practical, hands-on application principles. We also introduce the reader to a number of novel extensions and upgrades of R2R technology, designed to meet new and challenging requirements in the new generation of products.

Although we do not attempt to cover all aspects and possible variants of this widely used manufacturing tool, we sincerely hope that this volume will provide a solid foundation for students, practitioners and researchers already involved in R2R operations or those contemplating this process option in future development programs.

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1 Roll-to-Roll Manufacturing: An Overview

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1.1 Introduction

Roll-to-roll (R2R) manufacturing is an important manufacturing technology platform widely used for a host of applications and product categories, spanning many industries. These cover the gamut from traditional and mature technologies such as printing and silver halide photography to more novel application areas including flexible microelectronics [1–4], thin flexible batteries [5, 6], photovoltaics [7–10], and display [11–13]. A typical R2R production line, with standard coating, drying, and lamination steps, is depicted in Figure 1.1. This particular line, however, represents only one specialized process layout from within a multitude of manufacturing processes that can be broadly classified as R2R operations. A common thread in all these diverse manufacturing operations is that in all cases relatively thin and flat, film-type two-dimensional (2D) structures are processed continuously on a flexible moving web that is conveyed at some fixed speed between two or more rotating rollers. The web comprises an inert and flexible substrate on which a layer (or layers) of a functional material is applied by some means. The functional layer possesses some desired physical/chemical property that has special utility to its intended application. Many types of functional layers are applied in R2R operations reflecting the wide variety of applications utilizing this manufacturing platform. These include chemically sensitized layers used in traditional photography, ink layers used in various printing lines, optically refractive, diffusive, or collimating layers used in optical films for liquid crystal displays, photovoltaic layers used in flexible solar cells, barrier layers used in various packaging applications and magnetic layers used in magnetic tape, to name just a few.
The functional layers are often flat and featureless films applied by some common coating method onto a moving substrate. However, in some application areas, the functional layers can be patterned by standard printing methods or by various novel photolithographic, embossing [14], or other patterning techniques. The various printing techniques fall under the general category of additive patterning, while some photolithographic techniques, where excess material is removed, are generally classified as subtractive patterning methods. The patterned functional layers are designed to enable a particular function such as light collimation (as in the case of prism films used in liquid crystal displays [15]) or special fluid management (as in the case of microfluidic films [16]), and are either directly printed or replicated onto the moving substrate from a master roll or belt having a corresponding relief (“negative”) pattern. A wide variety of micro- and nano-patterning methods are highly compatible with a continuous web, R2R-type operation and have been described at length in the literature [17, 18]. Various printing methods such as inkjet printing, flexography, and screen printing are used extensively for producing patterned functional layers in R2R operations [19–22]. Patterning of the functional layer can also be achieved by self-assembly of block copolymers [23].

In addition to the functional layers, the final film structure often comprises additional so-called ancillary layers whose function is secondary to the intended application, but these layers are critical to the effective processability and successful function of the film product. Examples of ancillary layers include adhesion promoting layers, sometimes referred to as “primers” or “subbing layers,” that ensure good adhesion of the functional layer or an ancillary layer to the substrate or to another layer [24], antistatic layers [25] that dissipate static charges during conveyance and final use, various protective layers such as “hard coats” that protect the functional layers from environmental or mechanical damage [26], slip layers used to minimize friction during conveyance and end use, and barrier layers used to minimize contact with ambient gases, especially oxygen and water. (Barrier layers could be classified [27]).
as functional layers if the main function of the film product is to minimize contact with ambient gasses, e.g., in packaging applications.)

The substrate layer itself is often polymeric or paper-based although it could also be a metal foil or inorganic glass [27, 28]. Aside from being flexible, this layer serves as a physical foundation and carrier\(^1\) for the functional layer(s), which is often mechanically not sufficiently sturdy to withstand on its own mechanical deformations applied during the R2R manufacturing process or during its functional lifetime use. Thus, substrate materials must be generally dimensionally, mechanically, and environmentally stable under the conditions the film product is expected to withstand over its functional lifetime in order to ensure a durable and useful product. Some mechanical stiffness and rigidity are usually attained by making the substrate layer considerably thicker than the functional layer(s) and by ensuring that its glass transition temperature and melting point are well above the product’s processing or application temperature ranges. Although the bending stiffness of the film is significantly increased with an increase in thickness of the substrate layer, there is a myriad of factors that go into selecting the thickness and type of the substrate layer; the thickness is mostly dictated by product design considerations, but it can also adversely impact material cost, web conveyance, and winding, so proper selection of substrate thickness and type is critical to product performance, manufacturability, and cost. For many optical applications, the optical properties of the substrate such as transmittance, birefringence, and color are often critical to the performance of the film product [27] and must be carefully considered in selecting the appropriate substrate material for the application at hand. Otherwise, the substrate is expected to interfere as little as possible with the performance of the functional layer.

The origins of R2R manufacturing technology can be traced to the tail end of the Industrial Revolution in the second half of the 19th Century. In fact, the emergence of two traditional industries, printing and photography, is closely linked to advances and innovations in R2R manufacturing during the Industrial Revolution. A major boost to the evolution of mass printing was prompted by the invention of the rotary printing press in the 1840s by Richard Hoe [29]. Combining this invention with the earlier inventions of rolled paper and the steam engine made it possible to cost-effectively print large areas of paper continuously, thus launching mass-circulation newspapers and laying the foundation to the modern publishing industry. Similarly, the history of silver halide photography parallels and coincides with the emergence and evolution of R2R manufacturing. In the mid-19th Century, photographic plates were produced in a batch process by coating light-sensitive emulsions on glass. Consequently, silver halide photography was relatively expensive and out of

\(^1\) The substrate is sometimes referred to as film support, film base, or carrier layer.
reach of the average consumer. In the early 1880s, George Eastman and the newly founded Kodak (later to be named Eastman Kodak) Company developed a novel manufacturing process that facilitated the coating of light-sensitive materials on flexible substrates using a R2R operation that helped launch the mass production of photographic film [30]. The first step in the development of the R2R manufacturing process of photographic film was to coat photographic emulsions on a rolled paper substrate based on key inventions by William Walker and George Eastman [30]. This was followed by replacing paper with a clear cellulose nitrate substrate first proposed and patented by H. Reichenbach, one of Eastman’s early collaborators (see Figure 1.2), based on an earlier invention by H. Goodwin of a process for making cellulose nitrate film [31]. These pioneering developments in the manufacturing of photographic film led to the popularization of photography, making it accessible to the average consumer as well as creating a demand for cameras, film processing, and printing equipment and related consumer products. Indeed, many of the early developments and innovations in R2R manufacturing technology in the late 19th Century and first half of the 20th Century were prompted and driven by the fast growth of the photographic and printing industries but especially by the exacting demands of the photographic industry that required precise deposition of up to 24 thin light-sensitive layers on a fast-moving web as well as creating the need for advanced finishing methods and novel substrate technologies [32].

Today, many wide-ranging industries, including printing, paper, packaging, and photography, among others, benefit directly from the operational and cost advantages of the R2R manufacturing technology platform. Many focused attempts to adapt and extend R2R processing practices to various new technology areas, particularly in microelectronics, display, and photovoltaics, are currently underway in many research groups around the world [1–4, 7–13].

Figure 1.2 Drawing of a roll-to-roll coating process in Reichenbach’s 1889 patent.
Some common operational features of R2R processes are highlighted in Section 1.2 followed by a general discussion of cost and environmental, health, and safety considerations in Sections 1.3 and 1.4.

1.2 R2R Operation Overview

R2R operations are as varied and diverse as the markets and product categories they serve, but they share many underlying common features and operational principles. Figure 1.1 represents a typical R2R production line with conventional coating, drying, and lamination steps, but a more generic schematic layout of a R2R operation is shown in Figure 1.3. In this schematic a flexible web is conveyed between two rollers while passing through various process (converting) steps. An unprocessed web, comprising an uncoated or pre-coated substrate, is fed from a supply station (unwinder) wherein the raw or partially processed substrate is unwound from a supply roller and fed into the R2R machine (dashed frame). The raw substrate then undergoes a series of consecutive process (converting) steps (S1, S2, ...) while being conveyed at a controlled speed through the R2R machine.

The web, consisting of a substrate and deposited layers, is driven through the R2R machine by the winder and its conveyance is facilitated by a number of conveyance rollers or idlers (C) placed along its path. Tension in the conveyed web is controlled by the winder but is typically adjusted by one or more tension rollers (T) distributed within the R2R machine to insure flatness, planarity, and defect-free conveyance throughout the operation. We note that a single R2R line could have more than one unwinder if the operation comprises lamination.

Figure 1.3 Generic roll-to-roll operation with five converting steps (S1–S5), one tension roller (T), and two conveyance rollers (C).
or interleaving steps, as illustrated in Figure 1.1, but the line is always terminated by a single winder. The only exception here is for the case where the incoming substrate is protected by a sacrificial protective layer (“release liner”), which must be peeled off using a separate winder before the substrate is processed in the R2R machine.

Five converting steps are illustrated in the schematic layout of Figure 1.3, though the number of steps is arbitrary and usually greater than 1. A wide variety of converting steps are used in R2R operations, most of which involve the deposition and posttreatment of thin layers of some functional and ancillary materials on the moving substrate. Indeed, typical converting steps can be categorized by two main classes: (i) film-forming steps whereby a thin material layer(s) is deposited on the moving substrate and (ii) film enhancement steps whose function is mainly to consolidate, modify, and improve the performance of the deposited layer(s). Examples of common R2R film-forming steps include wet coating [33, 34], vacuum deposition [35, 36], printing [20, 21, 37], solvent casting, extrusion casting, and lamination, while typical film enhancement steps include drying [33, 34, 38], radiation curing [39–41], thermal curing, calendaring, micro- or nano-patterning [14, 17, 18], heat treatment, Corona discharge treatment [42], annealing, chemical treatment, cleaning, interleaving, and so on. Some steps may require a special environment (temperature, humidity, vacuum, nitrogen blanket, etc.) so the web moving through the corresponding station must be properly enclosed, which may present some challenges as discussed later. Figure 1.3 underscores the modular nature of R2R operations whereby converting steps (modules) can be added or removed from the production line as dictated by the special requirements of the film product.

As the web is conveyed at a constant speed through all converting steps, it is important to select a speed (equivalent to residence time) that satisfies all process elements to allow an overall robust operation. In this sense we say that the process steps are coupled and the final line speed is constrained by the slowest process step. This is the so-called rate-determining step for the R2R operation. If this is not possible, that is, if one or more steps must operate at very different speeds from the rest, the operation must be split into more than one line, each operating at different speed, or the web needs to run multiple times through the same line at different speeds. Such a “multi-pass” (or “multi-line”) operation is, of course, costlier than a single-pass operation and must be avoided if possible. Indeed, as discussed in Section 1.3, the selection of line speed is dictated not only by quality and operational considerations but also by cost considerations. Another factor, aside from line speed, that would require multi-line or multi-pass operation is process environment; for example, addition of vacuum deposition steps to a R2R line. Generally, confining a fast moving web in a vacuum atmosphere may be particularly challenging when combined with atmospheric pressure process steps, which may necessitate splitting the operation into an atmospheric pressure line and a vacuum deposition line.
Line speeds in R2R operations vary widely depending on the type of film being processed, the quality requirements, and the number of converting steps along the R2R line. For mature and commoditized technologies such as printing and various paper products, line speeds of up to 2000 m/min are not uncommon. But for more specialized application areas and advanced technologies with film products having complex and exacting layer structures with tight registration requirements, speeds of less than 10 m/min are often used. As discussed in Section 1.3, cost considerations dictate operating at the highest possible line speed, but product quality and processability will determine the limiting speed at which the line can be operated robustly; when operating above this limiting speed, film quality will not meet product specifications consistently. Several common rate-limiting effects that define the effective operational range for the film product are various flow instabilities (for wet coating), machine vibrations, drying load, radiation dosage, air entrainment, fluid delivery and pumping capacity (especially for viscous liquids), and deposition time (for vacuum deposition steps). Thus, identifying the optimal line speed range for a given product that satisfies both cost and quality requirements is key to an effective operation of the R2R line (see Section 1.3 for further discussion on this point).

Another “coupler” for the R2R operation is web tension, which is controlled throughout the line by the winder, but it can be adjusted locally by idler “tension” rollers distributed along the line (e.g., see Figures 1.1 and 1.3). Nonoptimal or nonuniform tension can give rise to various defects, such as wrinkling, coating lines, coated layer thickness nonuniformity, and deformation in the substrate and deposited layers, so it must be carefully monitored and controlled [43]. As the main object of the R2R operation is to produce defect-free films with uniform functional layers and optimal performance, in-line monitoring and control of certain key attributes is often necessary to reduce waste, improve yields, and lower manufacturing cost (see Section 1.3). General web handling considerations for R2R operations are discussed elsewhere in this volume [43].

The processed substrate is finally wound up into a master roll in the winder station on the output end of the R2R machine. The winder is also the driver pulling the web through the machine at the prescribed line speed and tension. The master roll is the final product roll prepared by the R2R operation. When it exceeds a certain size, it must be removed from the winder and “finished” in a separate operation to produce the final product. Finishing typically entails cutting the processed web down to the final product dimensions (singulation), which are often different from the full web dimensions. Other possible finishing steps include polishing, cleaning, quality inspection, packaging, and shipping. Finishing, which can add significantly to manufacturing cost (see Section 1.3), can be performed on-site in close proximity to the R2R machine or off-site closer to the end customer, depending on cost and logistic considerations.
It is common, for logistic reasons, to store the fully processed master roll in a wound (rolled) state for some time before finishing and shipping to customers. Also, if the product is finished off-site, product master rolls are commonly shipped to the finishing site before unwinding and cutting. A prolonged rolled storage, however, can impact product quality in three possible ways:

1) **Curl**: The final product could acquire some curl (curvature) and become non-planar [44].

2) **Core damage**: High winding pressures and stresses within the wound roll could damage the functional layers and produce a defective product if it is wound up under excessively high tension.

3) **Blocking**: The top layer (functional layer side of the film structure) could interact with or adhere to the backing layer on the bottom side of the film when they come in contact during rolled storage, thus damaging the final film product.

It is well known, based on the so-called core-set curl effect [44], that polymeric films tend to take up some curl and deviate from a desired planarity after being stored for some time in a wound (rolled) state. The extent of curling depends primarily on the winding diameter (related to core size), thickness of the film, storage time and conditions, and the mechanical and viscoelastic properties of the web materials and particularly the substrate, which is typically the thickest layer in the film structure. The effect can be significant under some conditions rendering the final product defective in some application areas. Similarly, storing the processed roll under finite tension can produce high compressive stresses within the wound roll [45–47] that could damage the functional layers and negatively impact the performance of the final product. These stresses and the resultant damage are highest near the core hence the term **core damage**. One possible remedy is to minimize winding tension and rolled storage time. However, too low winding tension could make the roll “unstable,” leading to “telescoping” (outward sliding of wound layers near the core area) and other problems, thus requiring a judicious choice of winding tension without compromising the quality of the final product. It is also desirable to minimize rolled storage time although it is often dictated by supply chain and logistics considerations. The problem of blocking, commonly associated with rolled storage, is not dependent on winding pressure per se but can be exacerbated by high winding pressures. This problem is typically resolved either by reformulating one of the layers in direct contact during winding or by adding an inert interleaving layer to physically separate the top and backing layers during rolled storage. All these effects and the corresponding quality and cost implications need to be carefully considered when selecting storage options for a product produced in an R2R operation.
1.3 Process Economics

There are two main reasons for the attractiveness and widespread use of R2R processes throughout many segments of the economy, compared with corresponding batch or sheet-to-sheet processes. First, such processes can readily accommodate high-volume, high-throughput operations, thus making them well suited for mass production of 2D film-type products. Second, R2R processes are highly cost effective by virtue of their high throughput and because all process steps in such operations are co-located in a single site and often conducted by a single production machine and fewer operators, unlike batch operations in which all or most process steps are performed independently from one another. The higher throughputs, simplified logistics and operation, and lower capital assets ultimately lead to lower manufacturing cost.

In order to examine the cost structure of the R2R process, it is necessary to define its daily production output, $Q_{R2R}$ (usually expressed in $m^2$/day):

$$Q_{R2R} = Y \cdot S \cdot W \cdot t$$  \hspace{1cm} (1.1)

where $Y$ is the yield fraction (<1) for the R2R process, $S$ is the line speed, $W$ is the effective (“coatable”) web width that directly relates to machine size and capacity, and $t$ is the effective daily run time (hr/day) for the R2R machine. Overall manufacturing cost, $C_{R2R}$ ($/day), can be expressed by

$$C_{R2R} = C_{AU} \cdot t + C_F + C_M \cdot Q_{R2R}$$  \hspace{1cm} (1.2)

$C_{AU}$ is the asset utilization cost (cost to run the R2R machine per hour), while $C_F$ is a fixed daily cost (e.g., asset depreciation, maintenance, utilities, clean room operation, etc.). $C_M$ represents the cost of materials and other consumables per square meter of final product. Thus, the unit manufacturing cost for the R2R process, $UMC_{R2R}$ ($/m^2$), of the film product takes the form

$$UMC_{R2R} = \frac{C_{R2R}}{Q_{R2R}} = \frac{C_{AU} \cdot t + C_F}{Q_{R2R}} + C_M = \frac{1}{Y \cdot S \cdot W} \left( \frac{C_{AU} + C_F}{t} \right) + C_M$$  \hspace{1cm} (1.3)

From inspection of Eq. (1.3), the three key operational parameters that directly contribute to cost are yield ($Y$), line speed ($S$), and effective web width ($W$); based on the simple relationship of Eq. (1.3), all three need to be maximized in order to lower $UMC_{R2R}$. However, these variables are generally interdependent—in particular, the yield function depends in some way on line speed and machine width, $Y = f(S, W)$; controlling product quality and uniformity is often more challenging at higher speeds and for wider webs. The effect of line speed on yield and $UMC_{R2R}$ is illustrated schematically in Figure 1.4, where an optimal operational range—the “process window”—is shown. Thus, a key challenge for process engineers is to maximize line speed while maintaining
acceptable yields and, specifically, identify the “process window” or the effective operational range for a given set of product specifications. Increasing the width of the web (~machine size) is often less practical or feasible because the machine size is tied up to a capital asset, and increasing the size of the machine could lead to high capital expenditure. Aside from the need to acquire a larger and costlier machine, it might also require relocating the manufacturing operation to a larger and more expensive physical structure. Also, controlling product quality and uniformity across wider webs is usually more difficult. The “process window” is generally defined as the actual range for all key operational (independent) process variables (e.g., S, temperature, UV dosage, line tension, and the like) that correspond to the highest yields, lowest \( UMC_{R2R} \), and, overall, to the most robust operation; the larger the “window,” the more robust the operation. It is finally noted that the cost advantage of an R2R operation over a corresponding batch process can be understood in a very simplistic way by assigning a very low effective line speed to the batch process, which would drive the UMC higher based on Eq. (1.3). A batch process could also have higher fixed and asset utilization costs.

If a particular product requires multiple passes through the R2R machine because of large differences in process conditions (especially line speed, environment, line tension, etc.) for the different converting steps, the final UMC for the R2R process becomes

\[
UMC_{R2R} = \sum_{i=1}^{n} UMC_{R2R,i} \tag{1.4}
\]
where $UMC_{R2R,i}$ is the unit manufacturing cost for the $i$th pass and $n$ is the total number of passes for the entire R2R operation. Each pass has a different yield ($Y_i$), line speed ($S_i$), and material cost ($C_{M,i}$) associated with it, but all other parameters ($W$, $C_{AU}$, $C_F$, $t$) are expected to remain the same for all passes if the same R2R machine is utilized. Thus, by implication, each additional pass adds to the final manufacturing cost associated with the R2R process, and limiting the number of passes should be generally cost advantaged and therefore highly desirable.

The final unit manufacturing cost of the finished product must include not only the cost of the R2R process but also the corresponding finishing costs. Indeed, the total unit manufacturing cost of the final finished product can be written as

$$UMC_p = UMC_{R2R} \cdot A_p + UMC_f$$

where $A_p$ is the actual area of the finished (cut) product and $UMC_f$ expresses the total cost of finishing per final cut product. This quantity depends on the particular finishing steps and conditions applied, and it contributes independently to yield losses ($1-Y_i$), which must be combined with yield losses associated with the R2R process ($1-Y$). Indeed, key contributions to manufacturing yield losses come from three main sources: (i) process (R2R)-induced defects ($1-Y_i$), (ii) finishing losses ($1-Y_f$), and (iii) defective raw materials. Process-induced defects can occur when the R2R process is operated outside its optimal range. For example, as discussed in Section 1.2, excessively high line speeds could induce a variety of disturbances such as mechanical vibrations, air entrainment, flow instabilities, insufficient drying or curing, and so on, leading to a defective product (see Figure 1.4). Likewise, out-of-range, spatially variable temperature or UV dosage and nonoptimal line tension could also induce a variety of defects in the final product. It is, therefore, important to identify optimal ranges, which define the “process window” (e.g., see Figure 1.4), for the key process variables to ensure a robust, defect-free, and cost-effective operation. Thus, continuous monitoring of the key process variables is essential for controlling the process and operating within its optimal range. Monitoring, however, must be conducted along and across the full web to ensure that the monitored process variable is uniform throughout the moving web. Variability along the moving web (machine direction ($MD$)) is often associated with different process disturbances compared with variations across the web (transverse direction ($TD^2$)), so changes along both principal directions must be fully monitored and established in order to identify the underlying root cause for the observed variability and/or defect. Variability along or across the web could lead to spatial nonuniformity of

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2 In some industries the term cross direction (CD) is used instead of TD.
the film product and corresponding yield losses. Process control requires also full or partial monitoring of key product attributes, which can be done online, that is, directly on the moving web, or offline, by removing some select sections of the processed web and testing independently from the R2R machine. Online monitoring has many advantages, including speed, more complete spatial resolution, and better integration with efficient open- or closed-loop process control strategies. But such monitoring is usually more capital intensive and not always easy to implement.

A common metric used to define process robustness is the process capability index [48, 49]. For a two-sided specification for a key performance variable (a dependent variable directly tied to the performance of the final product), this parameter is defined as

\[ CI_p = \frac{USL - LSL}{6\sigma} \]  

(1.6)

where USL is the upper specification limit, LSL is the lower specification limit, and \( \sigma \) is the standard deviation or variability of the performance variable. For one-sided specification, the process capability index takes the form

\[ CI_{p,\text{upper}} = \frac{USL - \mu}{3\sigma} \quad \text{For upper specification limit only} \]  

(1.7a)

\[ CI_{p,\text{lower}} = \frac{\mu - LSL}{3\sigma} \quad \text{For lower specification limit only} \]  

(1.7b)

where \( \mu \) is the mean value of the performance variable. If the process mean is not centered between USL and LSL for a two-sided specification, the process capability index of Eq. (1.6) is redefined as follows:

\[ CI_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right) \]  

(1.8)

It is generally recommended that the process capability index falls in the range 1–2 (corresponding to \( 3\sigma–6\sigma \) operation) to assure a well-controlled, robust operation, but the actual target for \( CI_p \) should depend on the particular product requirements and cost/yield tolerance.

Losses and waste from finishing steps can also contribute to a lower overall yield and higher manufacturing cost. As noted in Section 1.2, the final processed web, wound up into a roll by the winder, has to be “finished,” that is, cut down to the final product dimensions, inspected, packaged, and shipped out to customers. Finishing may also entail other steps such as polishing, cleaning, removal of interleaving layer, and so on, but most of the finishing losses are
usually related to the cutting step. There are three main sources of waste associated with cutting:

1) Diagramming losses—only a portion of the linear processed web can be cut into product (e.g., as in the case of a round final product that must be cut from a rectilinear web) and the leftover portion is waste.

2) Edge effects—edges are usually discarded because product quality falls off near the edges of the web (This is actually a R2R process control issue.)

3) Cutting damage—the cutting step, which often involves high stresses and strains [50], can damage some sections of the product, usually near the cut edges, and render the cut product defective. Damage can also be incurred by debris, generated during the cutting step, adhering to the cut film product. Minimizing cutting damage requires selection of appropriate cutting methodology and tools for the product at hand. Many cutting methodologies are known [50, 51], and these should be properly matched to the type of materials being cut, the required cutting precision, the available cutting infrastructure, and the economics of the process.

Another category of finishing losses corresponds to defects associated with rolled storage. As discussed in Section 1.2, rolled storage can induce three types of defects in the final product: high curl and deviations from planarity due to core-set curl [44], core damage associated with high winding pressures [45], and blocking, that is, interaction between the bottom and top layers in the film structure during rolled storage. The potential for yield losses during rolled storage requires careful consideration of storage options during the post-process finishing phase.

The final contribution to yield losses comes from defective raw materials. If any of the raw materials used in the R2R operation (substrate, functional layer components, ancillary layer components, etc.) is defective in some way, or if the materials become defective during storage (e.g., due to inadequate shelf life) before or after R2R processing, they will produce a defective product. These losses can be minimized by close inspection of the incoming materials, proper storage and containment of the materials, and close monitoring of key material properties before R2R processing.

1.4 Environmental, Health, and Safety Considerations

The cost and overall layout of R2R operations are often dictated by health, safety, environmental, and regulatory considerations. Two elements of R2R operations that are particularly susceptible to environmental challenges are solvent coating and drying steps and some chemical vapor deposition steps
involving hazardous gases or plasma. If the solvents used in wet coating are hazardous in liquid or vapor form, special steps must be taken to contain them in their storage and delivery systems and during solvent removal in the drying step to keep emission levels within the mandated limit. In addition, if the solvent vapor poses a potential fire or explosion hazard, its so-called low explosion limit (LEL) must not be exceeded during any steps of the R2R operation, and regulatory mandates must be strictly adhered to [52].

It is often desired to use volatile, low boiling point solvents in wet coating operations because of the ease with which such solvents can be removed from the coated web, which, in turn, corresponds to lower operational and capital costs. The drying step often requires long web stations (large footprint) and relatively high temperatures to ensure effective solvent removal [33, 38] (e.g., see Figure 1.1). The size/length of the drying station and the drying temperatures can be reduced substantially, and/or line speed can be increased with increase in solvent volatility (decrease in boiling point), thus decreasing the overall operational and capital costs. However, such solvents are often environmentally hazardous and more difficult to fully capture in the drying station, which results in higher emissions, so the operational and capital benefits of utilizing volatile organic solvents must be weighed against the potential environmental liabilities and the cost of solvent and vapor containment infrastructure mandated by environmental regulations. Aqueous systems are naturally preferred from an environmental standpoint, but such formulations are not always feasible in some application areas, and removal of moisture by drying can be quite challenging and costly [38].

Another commonly employed approach to get around potential solvent hazards is to replace the solvent-based formulation with a solvent-less formulation, such as a radiation-curable (or temperature-curable) resin system, whereby the coated resin is solidified (cured) by exposure to a suitable radiation at a desired dosage [39, 40], which eliminates the need to remove any residual solvent or reactant from the coated web. This approach eliminates the use of solvents and drying steps although various types of radiation could also carry some potential health risks of their own. Indeed, other potential environmental hazards in R2R operations include UV radiation (in a UV curing station), fire resulting from static electricity (when a dry web is rubbing against coated rollers), leaks of hazardous liquids or gases when stored or pumped through long delivery lines, bodily injury when working in close proximity to a fast moving web, and so on. All these potential hazards must be given full consideration when designing a safe and cost-effective R2R operation. For example, fire hazard due to static electricity can be minimized by adding a suitable antistatic layer [25] to the final film structure that can effectively dissipate static charges. Similarly, exposure to UV radiation can be eliminated by using suitable protective gear and by designing the UV station with proper radiation shields.