Organic Electronics 15 (2014) 1631–1640

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Characteristics and evaluation criteria of substrate-based manufacturing. Is roll-to-roll the best solution for printed electronics?

Jürgen Willmann, Daniel Stocker, Edgar Dörsam *

Institute of Printing Science and Technology (IDD), Technische Universität Darmstadt, Magdalenenstr. 2, 64283 Darmstadt, Germany

ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form 30 March 2014
Accepted 8 April 2014
Available online 26 April 2014

Keywords:
Printed electronics
Substrate transport
Sheet-to-sheet
Roll-to-roll
Substrate-based manufacturing

ABSTRACT

The vast majority of publications covering the manufacturing of printed electronics employ a web-fed roll-to-roll process. However, other principles of substrate transport are well established in printing science and industry. The focus on roll-to-roll in the scientific community therefore remains ambiguous. In an attempt to structure the discussion about upscaling organic electronics production, we extend existing classifications of substrate-based manufacturing, which is not limited to the field of printed electronics. Production processes can be classified by five key components: manufacturing technology, contact topology, substrate transport, substrate velocity, substrate feed and the degree of integration. This paper reviews four different substrate transport principles: roll-to-roll, sheet-to-sheet, sheets-on-shuttle and hybrid forms like roll-to-sheet. Besides basic working principles, both chances and limitations are discussed. Due to their individual complexity, a sound comparison ought not be reduced to a few key figures. In fact, the selection of the substrate transport requires an in-depth analysis of the individual production process. To aid decision-making, we introduce a hierarchy of 19 attributes covering aspects of production flexibility, quality, reliability, productivity and operations.

1. Introduction

Manufacturing organic electronics via printing technologies is based on the patterning of numerous specific layers onto a substrate in order to function as semiconductors, dielectrics or electroluminescent sources. Substrates itself are solid and planar materials onto which layers of other substances are applied. Depending on the application, substrates may have additional functions such as electrical insulation, conduction or physical encapsulation. Many branches of industries employ this principle in their manufacturing, e.g. graphical printing, foil coating, printed circuit boards and display manufacturing. In either case, a method for advancing the substrate through the production line is required. During display manufacturing, rigid glass-substrates are moved while functional materials are added [1]. For printing processes, flexible substrates like paper and plastic foils are transported between different printing units [2]. Printing machines utilise optimised and highly efficient principles of substrate transport. The most important substrates for printed electronics are glass and plastic foils like PET or PEN. In the future, other substrates like paper, metal or shaped substrates are conceivable.

The vast majority of publications covering manufacturing methods use a web-fed process and roll-to-roll became a slogan for high-throughput production of organic electronics [3–8]. Highly productive processes like the newspaper production are mentioned to prove the potential of printing technologies, albeit their disparate

* Corresponding author. Tel.: +49 6151162132.
E-mail address: doersam@idd.tu-darmstadt.de (E. Dörsam).

http://dx.doi.org/10.1016/j.orgel.2014.04.022
1566-1199/© 2014 The Authors. Published by Elsevier B.V.

requirements. Despite its significance, the different components of substrate-based manufacturing are currently not considered in the discussion about upscaling printed electronics production.

With device layouts and suitable materials being available, the research efforts should also be driven towards upscaling the laboratory-tested production. The design of a production system is influenced by a multitude of factors, which is why we find now to be the appropriate time to discuss their properties. Apart from the principle of transport, other components for substrate-based manufacturing can be identified to further structure the development efforts towards devices and products.

Diverse approaches are taken to transfer organic electronic production "from lab to fab" [9]. For instance, the influence of substrate materials are explored [10–12]. Several investigations address novel manufacturing technologies [13,6]. Additionally, the effect of the polymer material [9] as well as the fluid flow itself are studied [14].

The purpose of the present investigation in this context is to provide a holistic manufacturing classification for organic electronics. Classification facilitates the grouping of experiments and their comparability by a clarified communication [15]. Additionally, new fields of research can be identified to design efficient production processes [16]. Currently, several classification attempts for printed electronic production can be identified in the literature.

Søndergaard et al. focus on substrate transport principles and group published experiments into "true" roll-to-roll (R2R), R2R-"compatible" and non-R2R-processing [3]. Chang et al. mainly regard the manufacturing technologies and differentiate between subtractive and additive processes [17]. In order to compare manufacturing processes for printed electronics our classification incorporates the existing approaches and extends them by several other components.

The remainder of this paper is organised as follows. In Section 2 we introduce a classification of substrate-based manufacturing containing several key components. Section 3 outlines technical aspects, chances and limitations of four established substrate transport principles. Section 4 presents a hierarchy of criteria for the evaluation and selection of substrate transport principles based on requirements specific to the product. Section 5 summarises our findings and provides some concluding comments.

2. Classification of substrate-based manufacturing

Substrate-based manufacturing processes consist of six key components: manufacturing technology, contact topology, substrate transport, substrate velocity, substrate feed and the degree of integration. These components are mostly independent of each other and characterise any substrate-based manufacturing-process. Combining the components allows for several dozen possible manufacturing process designs. Hence, the current discussion about upscaling the production of printed electronics covers only a fraction of this solution space. Fig. 1 depicts the components and their corresponding characteristics. In the following sections, we describe the classification before we provide a more detailed overview of substrate transport principles.

The *manufacturing technology* describes the principle, by which a defined and distinct pattern is applied onto the substrate. Numerous manufacturing technologies can be used for printed electronics and many new technologies are feasible. We distinguish three main groups: additive, subtractive and structuring manufacturing technologies. Additive manufacturing technologies are for

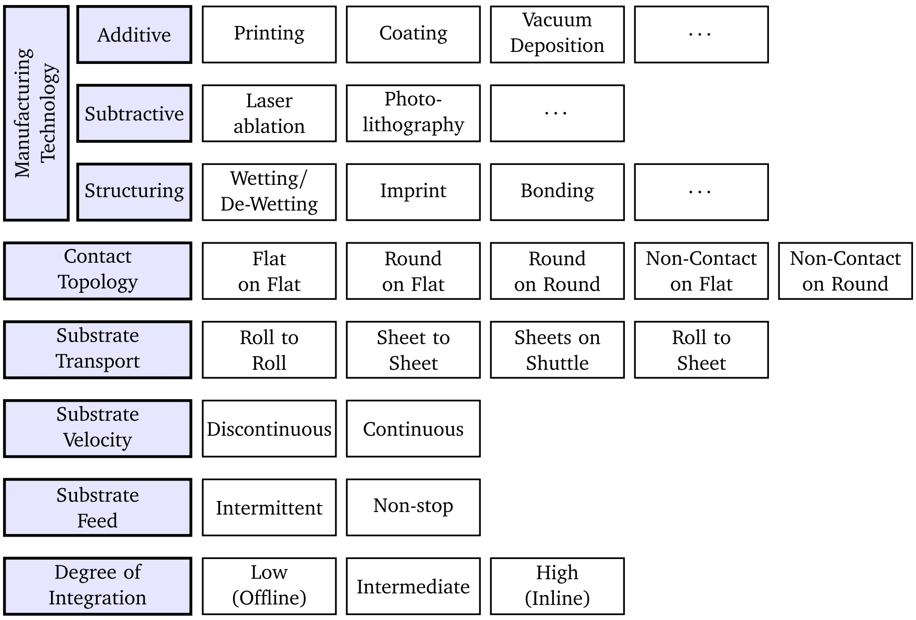


Fig. 1. Classification of substrate-based manufacturing processes.

example printing, coating or vacuum deposition. Various technologies for liquid phase processing have been developed and are widely used in graphical printing and the coating industry. Gravure printing, screen printing, offset printing and lithographic printing are common in the printing industry. The coating industry employs a multitude of different coating technologies; examples are blade coating or slot die coating. The technology of vacuum deposition is also used for printed electronics. Sputter methods and physical vapour deposition methods promise homogeneous layers. Examples for subtractive manufacturing technologies are laser ablation or photolithography. In this case, a part of the deposited material is removed from the substrate. The third category are structuring manufacturing technologies like wetting/de-wetting, imprinting or bonding. Besides the direct application of functional materials, external devices or other substrates can be bonded to the substrate via adhesive or welding techniques.

The *contact topology* describes the principle of transferring material onto the substrate. It has to be distinguished between methods with and without load transmission. The following methods evolved in graphical printing and have been the subject of continuous optimisation. The first printing machines were based on a flat-on-flat printing method, where the substrate is placed on a flat printing form and imprinted by a flat pressure plate, as shown in Fig. 2a. Further development led to round impression cylinders, hence the name round-on-flat. The flat printing form moves underneath the impression cylinder, on which the substrate is fixed, see Fig. 2b. Even higher output can be achieved by transforming the printing form into a cylindrical shape as well, dubbing this printing method round-on-round as shown in Fig. 2c. A similar differentiation is necessary for technologies without load transmission. The material is transferred while the ink-supplying part does not touch the substrate. Again, the printing plates can be either flat or round. Hence, we distinguish between non-contact-on-flat and non-contact-on-round manufacturing methods, which are represented by Fig. 2d and e. Examples for manufacturing technologies using this topology include inkjet printing, aerosol-jet printing and slot die coating.

The *substrate transport principles* describe the basic structure of moving the substrate without consideration of the technical realisation. As we will further elucidate in chapter 3, four different substrate transport principles can be identified: roll-to-roll, sheet-to-sheet, sheets-on-shuttle and roll-to-sheet.

The *substrate velocity* of the manufacturing process can be either continuous or discontinuous. Continuous substrate motion is achieved, if the momentary velocity of the substrate at every point inside the printing machine equates to the average substrate velocity throughout the manufacturing line. The velocity in standard sheet-fed and web-fed graphic printing machines remains constant. All printing units contain the same printing technology and therefore have the same optimal printing speed. For printed electronics, however, different manufacturing technologies are used for individual layers and thus, the optimal manufacturing speed deviates between the process steps. Setting up separate production lines for each process step is feasible, but further complicates the handling of material. Using substrate reservoirs is another option to buffer between manufacturing machines with different substrate velocities.

Two modes of *substrate feed* can be distinguished: non-stop- and intermittent production. Intermittent production occurs, if the process has to be halted after the substrate buffer is empty to allow for a refill. Afterwards, the machine continues with the next manufacturing cycle. The majority of printing machines operate in the intermittent mode. To achieve non-stop production, the substrate supply needs to be changed on the fly to avoid stoppage. Roll-to-roll printing machines can utilise

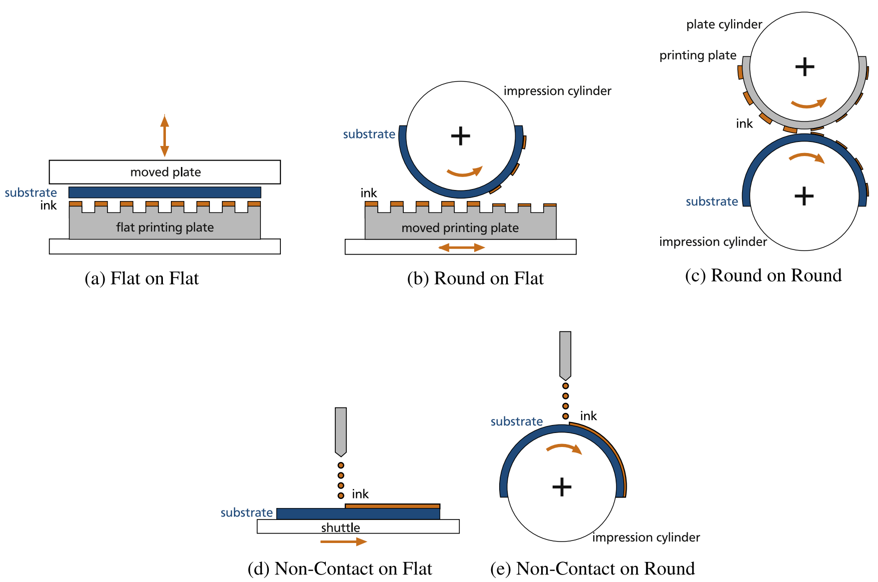


Fig. 2. Overview of contact topology.

an automatic reel change, which splices the new substrate roll onto the old substrate roll at maximum substrate velocity. Sheet-fed printing machines employ automatic pile changers to achieve non-stop production. The overall manufacturing process naturally becomes more productive with a non-stop substrate feed. The throughput is higher and the waste after the start of each manufacturing cycle can be minimised. Therefore, the non-stop mode is advantageous for a smooth production flow of high volumes.

The *degree of integration* measures how many production steps are incorporated in a single machine. The two extreme cases are inline and offline production. All layers are prepared, patterned and annealed without requiring a change of machinery: the production happens inline. In contrast to that the production is called offline, if every feature of the device is manufactured on separate machines. The intermediate case describes all production lines, where some, but not all, processes are manufactured on one machine. For example, the functional layers could be patterned in a coating machine, but the substrate is afterwards moved to a dedicated drying apparatus.

This manufacturing classification allows the comparability of experiments on a broader scale by including the production process as a whole. It can be intuitively applied to experiment descriptions in the literature and the nomenclature is based on common academic terms within the communities of both organic electronics and printing science. In the following section we focus on the aspect of substrate transport. Each of the four principles are covered in detail to allow for meaningful decision making with the evaluation criteria we will be presenting in Section 4.

3. Substrate transport principles

As mentioned above, the substrate can be moved through the production line by four basic principles: roll-to-roll, sheet-to-sheet, sheets-on-shuttle and roll-to-sheet [18]. While components like substrate velocity and substrate feed are important to classify substrate-based manufacturing processes, the principles of transport allow for more adaptation in regard to the properties of the final product.

The requirements for the substrate transport are mainly influenced by the specific manufacturing process and the desired product. The exact positioning of the substrate has to be guaranteed at every time to minimise registration errors in multilayered devices. Sensitive substrates furthermore require smooth material handling to avoid surface defects. Depending on the manufacturing technology, a minimal production velocity has to be maintained in order to ensure maximum layer quality. Different substrate transport principles facilitate production in an inert gas atmosphere or cleanroom, which may be required by some devices.

Keeping these particular requirements in mind, we are covering technical aspects, chances and limitations of the four substrate transport principles. Given the broad base of knowledge in the printing sciences, we focus our examination on printing processes and machines.

3.1. Roll-to-roll substrate transport

The substrate transport principle roll-to-roll is also known as reel-to-reel or web-fed printing. This substrate transport via web is characterised by a continuous substrate. The infeed unit peels the web off the reel and accelerates the substrate to machine speed. The infeed unit also allows the web to be aligned laterally and, as a result of the slight speed variations, adjusts the web tension to the substrate. Most of the commercial printing presses have a horizontal web travel and the web can be printed on from one or from both sides.

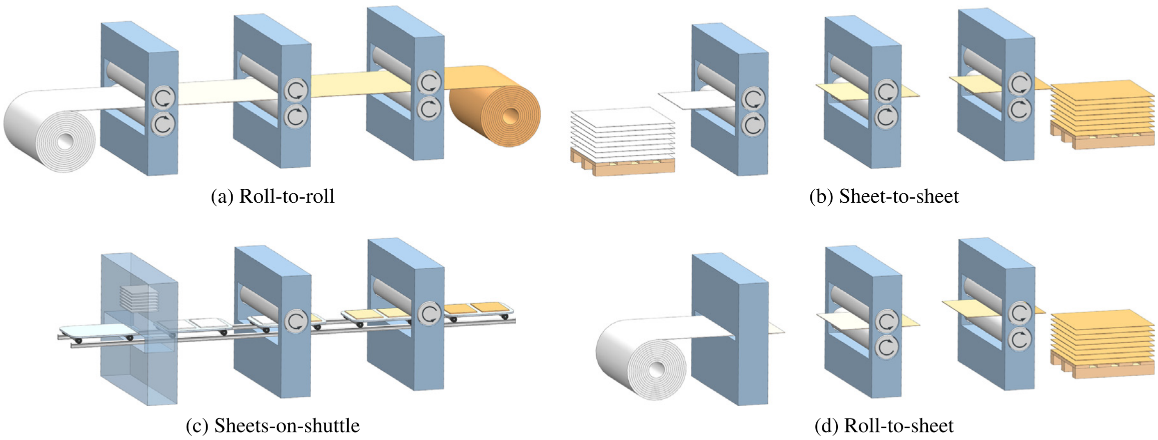
The web passes the printing units (in a graphical printing press up to ten printing units or more) and the fluids have to be dried in the drying unit with hot air, UV or IR. The chill roll assembly cools down the web. In the last step, the web can be rolled up to a new reel, or can be further processed. The final product is usually not desired to be a printed substrate reel. Hence, several cutting and folding steps are required, which can be integrated into the printing machine. Special variations of roll-to-roll machines are for example the multi-cylinder printing press (mostly combined with flexographic printing), where several printing units print on one big impression cylinder [19] or newspaper printing presses, where several webs being printed at the same time in vertical direction.

The challenge for the substrate transport is to ensure the precise movement of the substrate. Therefore, the web must be held at the required tension as soon as it leaves the reel [20]. Web tension control is an important function of any web-fed machine, because it limits the products quality as well as the machines production efficiency [19]. The roll-to-roll technology has several advantages over the other transport principles. The simple transport principle allows for affordable machine concepts. The comparatively quick set-up makes this technology easily handleable for laboratory-scale experiments. Another feature of the roll-to-roll technology is the continuous process, which allows a benefiting equilibrium process for both fluid delivery and fluid consumption. Current graphical printing machines demonstrate the potential of high productivity, but given the different requirements, they ought not be directly compared to organic electronics manufacturing.

For high-quality printing with a high-precision registration, roll-to-roll machines require complex registration control systems, because roll-to-roll machines have no mechanical lead edge for lateral substrate alignment. In large roll-to-roll machines, the substrate can be more than hundred meters long. With the differences of temperature, the distortion of the web lengthwise and laterally poses a big challenge.

3.2. Sheet-to-sheet substrate transport

The sheet-to-sheet process is also known as sheet-fed printing. The substrate has a rectangular form and the size differs between a few cm^2 and several m^2 in printing machines. As shown in Fig. 3b, the sheets are stored in a sheet pile. The sheet feeder lifts the top sheets and put them as an overlapping stream to the feet table. The sheets are aligned at the front and side edge, before they are



(a) Roll-to-roll (b) Sheet-to-sheet

(c) Sheets-on-shuttle (d) Roll-to-sheet

Fig. 3. Overview of substrate transport principles.

grabbed by the sheet grippers. The sheets are accelerated to the circumferential speed of the printing press. They are transferred through the machine from the first impression cylinder to the transfer drum and to the storage drum, etc. by means of gripper systems. The printed sheets are transferred through the drying unit to the delivery unit by a delivery chain after passing the grippers of the last cylinder. The grippers of the delivery chain release the sheets. An air-stream slows them down and pushes them down vertically to deposit the sheets on the delivery pile.

The control of the registration in a sheet-fed machine is less complex as in a web-fed machine. This is caused by the significantly lower distortion in wider substrates compared to web-fed printing. Sheets have a maximum length of around two meters. Additionally, the alignment in a sheetfed machine is very exact. Furthermore, a sheet-process is more flexible, because single process steps, such as drying, curing or vacuum annealing, can be externalised. Controlling the rejections is relatively simple, because single sheets of inferior quality can be sorted out directly in the machine. The productivity of graphical printing machines ranges from low to high. However, the machine speed is limited due to the gripper kinematics and the mechanical limitations of the substrates. The machine speed of web-fed machines can be around three times higher. Furthermore, the very precise registration demands complex mechanics. Gripperless sheet-to-sheet machines are available, albeit incapable of reaching comparable printing speeds.

3.3. Sheets-on-shuttle substrate transport

The sheets-on-shuttle substrate transport is also known as sheets-on-carrier. Sheets-on-shuttle allows the transportation of substrates without straining them. This makes it possible to transport very sensitive materials like DVDs and Blu-ray discs or substrates for organic electronics like wafers or thin foils. In a first step, the substrate has to be placed on the shuttle. Before the shuttle can be accelerated to the machine speed, the substrate has to be aligned relatively to the shuttle and the substrate has to be fixed on the shuttle. To accelerate the shuttle, the machine requires a precise fit to the shuttle. This can for example be realised with a rack and pinion drive.

As shown in Fig. 3c, the shuttles move with machine speed through the printing units, which have no impression cylinder, because the shuttles adopt their function. The contact topology in this figure is round-on-flat. The shuttles can be moved through other processing units like drying and curing. At the end of the process, the substrates have to be unloaded from the shuttles before being piled up. To reduce idle times, more than one shuttle is used. Machines based on sheets-on-shuttle substrate transport are realised in a cycle to minimise the travel of empty shuttles.

The chances of this technology are the possibility to transport a big variety of substrates in one machine, such as Blu-ray discs, wafers or other sensitive substrates. The substrates are being less strained and their distortion is reduced. This allows for highly precise movement and positioning. Additionally, this principle of substrate transport can be combined with many different technologies like printing processes or vacuum processes. The limitations of the shuttled transport are on the one hand the limited machine speed and on the other hand the limited size of the substrates. Until recently, there was little need for fast and big machines employing this transport principle. Therefore, the development and adaptation for organic electronics manufacturing is in the earlier stages. Furthermore, the material handling to and from the shuttle is more complex than in the other principles.

3.4. Hybrid forms of substrate transport

The hybrid principles of substrate transport are combinations of the already described methods, given the constraint of decreasing sheet size. Currently, roll-to-sheet is the only combination utilised in the graphic printing industry. Lower wholesale prices of substrate rolls compared to sheets enables cost-effective production. This hybrid principle of substrate transport is illustrated in Fig. 3d.

The process is similar to sheet-to-sheet printing. In contrast to that, the substrate is delivered as a web, which is accelerated to machine speed. The first process step is to singulate individual substrate sheets, which are transported to the feed table. The following process steps correspond to a sheet-to-sheet printing press.

Employing the roll-to-sheet principle permits the combination of cheaper substrate rolls with the higher accuracy and flexibility of the sheet-fed process. The printing company may use the standard post-press equipment without investing in new machines. On the other hand, the cutting unit and more complex material transport system require additional investments. Additionally, the alignment of the sheets is further complicated by imperfect cutting edges.

Combining the advantages of varying principles are the benefit of hybrid forms of substrate transport. Broadening the perspective to include the complete value chain, as opposed to a single printing machine, illustrates the potential of this approach. The base material of any substrate-based manufacturing process like foils and paper is produced on rolls, whereas the final product is sold as sheets of varying size containing individual devices. Hence, at least one singulation step is required in the value chain. Material costs, logistics or general product requirements however influence its optimal point and therefore may differ between production processes.

Given the various principles of substrate transport, the question of their selection becomes apparent. Unparalleled demands in terms of accuracy, consistency and product diversity remain the main challenges for printing electronic devices. Aspects like production flexibility at a consistently high quality while maintaining process reliability are paramount for successful mass-production. Additionally, no practical long term experiences exist. Therefore, it is not feasible to compile a general list of requirements for substrate transport principles. Each application – e.g. OPV, OLED or OFET – calls for different qualities [21]. Requirements of both the product and the overall production process have to be carefully assessed to arrive at a decision. In the following section, we establish a comprehensive hierarchy of such criteria. Therefore, the focus switches from technical aspects of substrate transport to the requirements of successfully manufacturing organic electronics.

4. Evaluation criteria for substrate transport principles

With regard to the individual complexity of all principles, we can not present a comparison on the basis of a few key figures. In fact, the selection of the substrate transport principle requires an in-depth analysis of the individual production process and the requirements of the product itself. Numerous attributes have to be taken into consideration. Clustering the parameters in a hierarchic structure can illustrate dependencies and simplify the decision-making procedure. Based on works about the selection of machine tools, five main criteria are established: flexibility, quality, reliability, productivity and operations [22]. All identified attributes are assigned to these nonspecific criteria and can be applied on the substrate transport principles as shown in Fig. 4. In the following, we focus on possible product scenarios rather than quantitatively comparing the described principles. Furthermore, cost aspects will only marginally be discussed in favour of technical aspects and general feasibility.

4.1. Flexibility

Production flexibility gained recognition during the 1980s and its implementation remains an active topic in manufacturing science. The machine level is the basis for production flexibility in general. Flexibility can be regarded as "versatility" and a gain in production options [23]. Volatile demand and short storage times increase the need for flexibility and its return by reducing the necessary planning periods.

Smaller minimum *order quantities* are seen as a key-advantage of printed electronics in comparison with silicon processing [21]. Lower tooling costs allow production at optimal costs at lower quantities. However, this aspect is not equally important for all printed electronic products. Whereas standalone photovoltaic cells are more likely to be produced in large quantities and with little diversity, an integrated product could benefit from smaller production runs. The prospect of lower order volumes could also

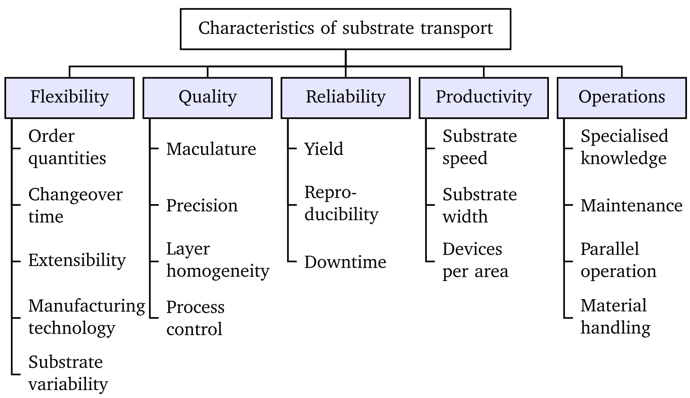


Fig. 4. Evaluation criteria for the selection of substrate transport principles for the production of OPV, OLED and OFET.

strengthen the marketing opportunities of integrated circuits in RFID-applications.

Smaller production runs cause more frequent changeovers, but do not influence the individual *changeover time* of the printing process. Lower changeover times can lead to an increase in machine capacity and availability, which is beneficial for both product and volume flexibility [24]. Sub-optimal barrier properties of current plastic substrates cause a loss of performance over time. Organic electronics are ''perishable'' goods and therefore, manufacturing products to stock in large numbers is not a sustainable option.

Combining all necessary manufacturing steps into one inline-production is the long-term goal of printed electronics. Therefore, the printing machine requires a high degree of *extensibility*, which might differ between substrate transport technologies. However, the need for extensibility is highly dependent on the characteristics of the product. Lighting applications and energy generation are likely to have longer product-cycles than displays, integrated circuits or consumer photovoltaics.

The *manufacturing technology* plays a viable role in the success of a production process. Currently, gravure printing is widely utilised (OPV: [25,26], OLED: [27,28], OFET: [29–31]). Specific features and layers however are often printed by means of flexographic printing (OPV: [32,33], OFET: [34,29]). Screen-printing is mostly used to manufacture organic photovoltaic [35,6], but source and drain contacts of transistors have also been patterned with this process [36]. Inkjet printing is also employed in various experiments (OPV: [37–39], OFET: [40,41]). Therefore, a substrate transport principle should be able to incorporate several printing processes to avoid a lock-in in case of newer developments.

The search for a suitable substrate is not yet complete. Higher *substrate variability* increases the product flexibility of the printing machine. Different products might require different thicknesses or material elasticities and the substrate transport principle ought to adapt to these requirements. Currently, most experiments use thin plastic foils (PET: [32,25,8,29]. PEN: [42]. PES: [43]) or paper [33,10]. Changes in the width of the substrate are covered under the criteria of productivity.

4.2. Quality

Highest possible quality is mandatory in semiconductor manufacturing. Contrary to graphical printing, the properties of organic electronics can usually not be controlled directly by the human eye. However, this optical boundary has been the traditional goal of optimisation in the development of printing processes. The requirements of functional printing demand for a new dimension of precision and homogeneity in manufacturing.

Apart from the effects on the performance of the final product, increasing quality can lead to decreasing manufacturing costs. The *maculature* denotes the amount of unusable material, which is produced during both start-up and operation of a printing process [2]. The printing unit does not reach a state of equilibrium immediately after start-up, making adjustments to the process parameters necessary. ITO-sputtered foils are widely used in OPV-manufacturing and amount to a large share in material costs [35,44–46]. The most suitable substrate transport principle might influence this process and reduce the changeover times as a side-effect.

The properties of organic electronics are mainly influenced by the *precision* of its features. This attribute covers both the registration error of multi-layer devices and the structural resolution of the printed patterns. Consistently small channel lengths reduce switching speed and the operating voltage in field-effect transistors [47]. Photovoltaic cells have lower requirements in terms of structural resolution, the registration error however directly influences the device performance. Minimising the overlap of all layers maximises the active area of the device [25,48,44].

Homogenous fluid-layers are less important in graphical than in functional printing. Small irregularities in thickness remain unrecognised by the human eye. The functionality of organic electronics however depends critically on a high *layer homogeneity*. Pin-holes lead to short circuits [49]. Varying thickness causes irregular illumination intensities in OLEDs and diverging efficiency levels in OPVs [50]. Multi-layer devices with thin dielectrics furthermore require a low surface roughness to avoid short-circuits between electrodes [51,12].

High quality requirements in combination with high material costs demand for continuous and immediate *process control*. Deviations in process quality are undetectable before the fluid application in the printing unit. Registration errors, false line widths and layer inhomogeneities hence need to be closely monitored. The integration of control units and automated quality assurance systems are critical for a high production yield. Reworks on flawed devices are impossible in semiconductor manufacturing [52].

4.3. Reliability

Reliability is commonly associated with the life expectancy of the product. However, we deem the reliability of the production process as more significant for the comparison between substrate transport principles. Life expectancy is influenced by properties of the semiconducting materials, the barrier capabilities of the substrate and environmental influences. Thereby, we define reliability as the ability of the printing process to produce devices of constant and predictable quality.

The ratio of usable products to theoretically manufacturable products in a production process is called *yield* [53]. It is a key figure for evaluating and comparing semiconductor manufacturing processes [54]. The yield is usually divided into three main components: process yield, test yield and assembly yield. We suggest to transfer these components to the field of printed electronics. Process yield denotes the ratio of successfully printed substrate area. Test yield is the percentage of functional devices before the cutting process and assembly yield the percentage of actually sellable devices. The overall process yield is calculated as the product of all three components [55].

Economic estimations for OPVs assumed an overall manufacturing yield of up to 95% [56]. A yield that high will require several iterations of optimisations to reduce the systematic errors of the production process [55]. Early experiments however already reported a yield of 79% for screen-printed photovoltaic cells [35]. Statements about the yield of printed transistors are scarce in the literature. A value of 75% was reported for a roll-to-roll printing process [57].

Functional printing does not award unique copies of devices, but requires a high *reproducibility* to predict and calculate their performance. The energy generation over the life-cycle of OPVs is crucial for their economic viability [58]. Sensitive applications like food or drug monitoring warrant a high level of trust by the customers. Furthermore, the reproducibility has to be guaranteed between production runs. Environmental influences in the printing room have negative influences and might deviate between substrate transport principles.

The importance of machine availability for its profitability has already been established for the changeover times [2]. *Downtime* during operations is another influence factor. Calibration, maintenance intervals and refilling the substrate supply are possible causes for production downtime. Mechanical differences between substrate transport principles might benefit a reduction of these intermissions to increase process reliability.

4.4. Productivity

High productivity potential of printing processes is widely regarded as a main success driver for organic electronics [59]. Measuring the productivity reveals interdependencies between the different criteria. *Print speed* and *substrate width* can be used to calculate the patterned area. However, an increase in productivity can also be achieved by miniaturisation of the structures and thus increasing the number of *devices per area* [60]. This approach is feasible for integrated circuits, but not for large-area electronics like OPVs and OLEDs.

4.5. Operations

The operations-criteria contains characteristics, which become significant during the interaction of employees with the machine or the collaborative production with other machines. Unlike the attributes of productivity, these characteristics are not directly measurable. Technological difficulties in setting-up and calibrating the machine could require *specialised knowledge* depending on the substrate transport principles, which could be distinguished by their degree of automation. ''Multi-trained employees'' are able to adjust to new measurement devices and are an important part of a flexible production [61]. Individual skill and knowledge however are not the only components of quick *maintenance*. The modularity of the machine, its accessibility and the complexity of its mechanical elements at best support the employees to ensure smooth production.

Inline production means that all necessary manufacturing steps are included in one continuous process. However, many current lab-scale experiments employ long drying and annealing times lasting from several seconds [30,11] up to minutes [62,29,36]. Setting up a *parallel operation* of the longest steps might help to reduce the overall manufacturing time. Furthermore, the process could become more robust against machine failures. Achieving such a parallelisation requires easy *material handling* between processing stages. Thus, the separation point directly influences the ability of the substrate transport to allow for an internally flexible and adjustable production line.

5. Conclusion and outlook

In Section 2 we introduced a classification of substrate-based manufacturing and its corresponding components. These six components are meant to be universally applicable for many substrate-based manufacturing processes. We identified the substrate transport principle as a key component. In Section 3 we presented and evaluated alternatives to roll-to-roll transport. We established that these alternatives are widely-used in the field of graphical printing and other industries, but are underrepresented in the development of organic electronics. However, we found a general recommendation for one specific transport principle to be infeasible. Rather, an in-depth analysis of the product's requirements and the individual production process is necessary. In Section 4 we therefore presented 19 general evaluation criteria covering aspects of production flexibility, quality, reliability, productivity and operations.

This article serves as a theoretical framework for substrate-based manufacturing including, but not exclusive to the production of printed electronics. Further research efforts should concentrate on systematic comparisons of the components, which we presented in this manufacturing classification. Thus, a decision making process could be iteratively developed on the basis of a specific product.

The optimal singulation point in the manufacturing of organic electronics should also be investigated in detail. Overall, the substrate transport principle is just a single aspect in the effort of upscaling and optimising production. Not all components of substrate-based manufacturing are yet fully understood [63].

We demonstrated the complexity of selecting a transport principle for substrate-based manufacturing of organic electronics. Hence, the question posed in the title of this paper can not be conclusively answered. However, we established several limitations of the widely used roll-to-roll principle and presented promising alternative approaches. The sheets-on-shuttles principle is actively developed and meaningful results can be expected.

Additionally, an extensive body of knowledge has been developed and continuously extended for silicon-based semiconductor manufacturing during the last decades [64]. We believe that transferring both theoretical and practical methods like yield learning and modelling could greatly benefit the field of organic electronics. Furthermore, some of the recent requirements in the manufacturing of printed electronics were already present in the graphic printing industry. Challenges like smooth substrate handling and constant substrate velocity while maintaining high productivity have been overcome. However, the requirements regarding patterning precision and the degree of cleanliness remain unparalleled. Thus, we encourage the community to discuss the upscaling of laboratory-tested organic electronics production with respect to the broad variety of substrate-based manufacturing.

Acknowledgements

The authors gratefully acknowledge the financial support by the Bundesministerium für Bildung und Forschung (BMBF) in the Spitzencluster "Forum Organic Electronics". The authors appreciate the support by the InnovationLab GmbH, Heidelberg.

References

[1] R. Chen, Liquid Crystal Displays: Fundamental Physics and Technology, John Wiley & Sons Ltd., 2011.
[2] H. Kipphan, Handbook of Print Media: Technologies and Production Methods, Springer, 2001.
[3] R.R. Søndergaard, M. Hösel, F.C. Krebs, Roll-to-roll fabrication of large area functional organic materials, J. Polym. Sci. Part B: Polym. Phys. 51 (1) (2013) 16–34.
[4] Y. Galagan, I. de Vries, A. Langen, R. Andriessen, W. Verhees, S. Veenstra, J. Kroon, Technology development for roll-to-roll production of organic photovoltaics, Chem. Eng. Process.: Proc. Intensification 50 (5) (2011) 454–461.
[5] H. Park, M. Kang, S. Ahn, L. Guo, A facile route to polymer solar cells with optimum morphology readily applicable to a roll-to-roll process without sacrificing high device performances, Adv. Mater. 22 (35) (2010) E247–E253.
[6] F. Krebs, T. Tromholt, M. Jørgensen, Upscaling of polymer solar cell fabrication using full roll-to-roll processing, Nanoscale 2 (6) (2010) 873–886.
[7] J. Noh, D. Yeom, C. Lim, H. Cha, J. Han, J. Kim, Y. Park, V. Subramanian, G. Cho, Scalability of roll-to-roll gravure-printed electrodes on plastic foils, IEEE Trans. Electron. Pack. Manuf. 33 (4) (2010) 275–283.
[8] M. Jung, J. Kim, J. Noh, N. Lim, C. Lim, G. Lee, J. Kim, H. Kang, K. Jung, A. Leonard, J. Tour, G. Cho, All-printed and roll-to-roll-printable 13.56-MHz-operated 1-bit RF tag on plastic foils, IEEE Trans. Electron Dev. 57 (3) (2010) 571–580.
[9] R. Po, A. Bernardi, A. Calabrese, C. Carbonera, G. Corso, A. Pellegrino, From lab to fab: how must the polymer solar cell materials design change? – an industrial perspective, Energy Environ. Sci. 7 (3) (2014) 925–943.
[10] B. Peng, P.K. Chan, Flexible organic transistors on standard printing paper and memory properties induced by floated gate electrode, Org. Electron. 15 (1) (2014) 203–210.
[11] C. Koidis, S. Logothetidis, C. Kapnopoulos, P. Karagiannidis, A. Laskarakis, N. Hastas, Substrate treatment and drying conditions effect on the properties of roll-to-roll gravure printed PEDOT-PSS thin films, Mater. Sci. Eng.: B 176 (19) (2011) 1556–1561.
[12] C. Lee, H. Kang, C. Kim, K. Shin, A novel method to guarantee the specified thickness and surface roughness of the roll-to-roll printed patterns using the tension of a moving substrate, J. Microelectromech. Syst. 19 (5) (2010) 1243–1253.
[13] F. Jakubka, M. Heyder, F. Machui, J. Kaschta, D. Eggerath, W. Lövenich, F.C. Krebs, C.J. Brabec, Determining the coating speed limitations for organic photovoltaic inks, Sol. Energy Mater. Sol. Cells 109 (0) (2013) 120–125.
[14] Y. Diao, B.C. Tee, G. Giri, J. Xu, D.H. Kim, H.A. Becerril, R.M. Stoltenberg, T.H. Lee, G. Xue, S.C. Mannsfeld, et al., Solution coating of large-area organic semiconductor thin films with aligned single-crystalline domains, Nat. Mater. 12 (7) (2013) 665–671.
[15] J. Browne, D. Dubois, K. Rathmill, S.P. Sethi, K.E. Stecke, Classification of flexible manufacturing systems, FMS Mag. (2) (1984) 114–117.
[16] I. McCarthy, Manufacturing classification: lessons from organizational systematics and biological taxonomy, Integr. Manuf. Syst. 6 (6) (1995) 37–48.
[17] J. Chang, X. Zhang, T. Ge, J. Zhou, Fully printed electronics on flexible substrates: high gain amplifiers and DAC, Org. Electron. 15 (3) (2014) 701–710.
[18] J. Willmann, E. Doersam, D. Stocker, P. Schmidt, Printed electronics beyond roll-to-roll – a reflection of alternative substrate transport technologies, in: Proceedings of the Fall Meeting of the Material Research Society (MRS), 2012.
[19] Flexographic Technical Association, Flexography: Principles & Practices, fiveth ed., Flexographic Technical Association, 2000.
[20] Gravure Association of America, Gravure: Process & Technology, second ed., Gravure Association of America, 2003.
[21] J.R. Sheats, Manufacturing and commercialization issues in organic electronics, J. Mater. Res. 19 (7) (2004) 1974–1989.
[22] J. Tsai, H. Cheng, S. Wang, Y. Kao, Multi-criteria decision making method for selection of machine tool, International Symposium on Computer Communication Control and Automation (3CA), vol. 2, IEEE, 2010, pp. 49–52.
[23] A. Baykasoğlu, Quantifying machine flexibility, Int. J. Prod. Res. 47 (15) (2009) 4109–4123.
[24] J. Olhager, Manufacturing flexibility and profitability, Int. J. Prod. Econom. 30 (31) (1993) 67–78.
[25] P. Kopola, T. Aernouts, R. Sliz, S. Guillerez, M. Ylikunnari, D. Cheyns, M. Valimaki, M. Tuomikoski, J. Hast, G. Jabbour, R. Myllylä, A. Maaninen, Gravure printed flexible organic photovoltaic modules, Sol. Energy Mater. Sol. Cells 95 (5) (2011) 1344–1347.
[26] J. Ding, A. De La Fuente Vornbrock, C. Ting, V. Subramanian, Patternable polymer bulk heterojunction photovoltaic cells on plastic by rotogravure printing, Sol. Energy Mater. Sol. Cells 93 (4) (2009) 459–464.
[27] D. Chung, J. Huang, D. Bradley, A. Campbell, High performance, flexible polymer light-emitting diodes (PLEDs) with gravure contact printed hole injection and light emitting layers, Org. Electron. 11 (6) (2010) 1088–1095.
[28] S. Tekoglu, G. Hernandez-Sosa, E. Kluge, U. Lemmer, N. Mechau, Gravure printed flexible small-molecule organic light emitting diodes, Org. Electron. 14 (12) (2013) 3493–3499.
[29] H. Kempa, M. Hambsch, K. Reuter, M. Stanel, G. Schmidt, B. Meier, A. Hübler, Complementary ring oscillator exclusively prepared by means of gravure and flexographic printing, IEEE Trans. Electron Dev. 58 (8) (2011) 1–5.
[30] J. Noh, M. Jung, K. Jung, G. Lee, J. Kim, S. Lim, D. Kim, Y. Choi, Y. Kim, V. Subramanian, Fully gravure-printed D flip–flop on plastic foils using single-walled carbon-nanotube-based TFTs, IEEE Electron Dev. Lett. 32 (5) (2011) 638–640.
[31] P. Heljo, K.E. Lilja, H.S. Majumdar, D. Lupo, High rectifier output voltages with printed organic charge pump circuit, Org. Electron. 15 (1) (2014) 306–310.
[32] F. Krebs, J. Fyenbo, M. Jørgensen, Product integration of compact roll-to-roll processed polymer solar cell modules-methods and manufacture using flexographic printing, slot-die coating and rotary screen printing, J. Mater. Chem. 20 (41) (2010) 8994–9001.
[33] A. Hübler, B. Trnovec, T. Zillger, M. Ali, N. Wetzold, M. Mingebach, A. Wagenpfahl, C. Deibel, V. Dyakonov, Printed paper photovoltaic cells, Adv. Energy Mater. 1 (6) (2011) 1018–1022.
[34] G. Schmidt, M. Bellmann, B. Meier, M. Hambsch, K. Reuter, H. Kempa, A. Hübler, Modified mass printing technique for the realization of source/drain electrodes with high resolution, Org. Electron. 11 (10) (2010) 1683–1687.
[35] F. Krebs, M. Jørgensen, K. Norrman, O. Hagemann, J. Alstrup, T. Nielsen, J. Fyenbo, K. Larsen, J. Kristensen, A complete process for production of flexible large area polymer solar cells entirely using screen printing – first public demonstration, Sol. Energy Mater. Sol. Cells 93 (4) (2009) 422–441.
[36] A. de la Fuente Vornbrock, D. Sung, H. Kang, R. Kitsomboonloha, V. Subramanian, Fully gravure and ink-jet printed high speed pBTTT organic thin film transistors, Org. Electron. 11 (12) (2010) 2037–2044.
[37] A. Lange, W. Schindler, M. Wegener, K. Fostiropoulos, S. Janietz, Inkjet printed solar cell active layers prepared from chlorine-free solvent systems, Sol. Energy Mater. Sol. Cells 109 (2013) 104–110.
[38] A. Lange, A. Hollaender, M. Wegener, Modified processing conditions for optimized organic solar cells with inkjet printed P3HT:PC61BM active layers, Mater. Sci. Eng.: B 178 (5) (2013) 299–305.
[39] Y. Galagan, E.W. Coenen, R. Abbel, T.J. van Lammeren, S. Sabik, M. Barink, E.R. Meinders, R. Andriessen, P.W. Blom, Photonic sintering of inkjet printed current collecting grids for organic solar cell applications, Org. Electron. 14 (1) (2013) 38–46.
[40] M. Benwadih, A. Aliane, S. Jacob, J. Bablet, R. Coppard, I. Chartier, Integration of a graphene ink as gate electrode for printed organic complementary thin-film transistors, Org. Electron. 15 (2) (2014) 614–621.

[41] T. Le, Z. Lin, R. Vyas, V. Lakafosis, L. Yang, A. Traille, M.M. Tentzeris, C.-p. Wong, Inkjet printing of radio frequency electronics: design methodologies and application of novel nanotechnologies, J. Electron. Pack. 135 (1) (2013) 011007.
[42] J. Verilhac, M. Benwadih, A. Seiler, S. Jacob, C. Bory, J. Bablet, M. Heitzman, J. Tallal, L. Barbut, P. Frère, et al., Step toward robust and reliable amorphous polymer field-effect transistors and logic functions made by the use of roll to roll compatible printing processes, Org. Electron. 1 (3) (2010) 456–462.
[43] M. Voigt, A. Guite, D. Chung, R. Khan, A. Campbell, D. Bradley, F. Meng, J. Steinke, S. Tierney, I. McCulloch, et al., Polymer field-effect transistors fabricated by the sequential gravure printing of polythiophene, two insulator layers, and a metal ink gate, Adv. Funct. Mater. 20 (2) (2010) 239–246.
[44] R.R. Søndergaard, M. Hösel, M. Jørgensen, F.C. Krebs, Fast printing of thin, large area, ITO free electrochromics on flexible barrier foil, J. Polym. Sci. Part B: Polym. Phys. 51 (2) (2013) 132–136.
[45] Y. Galagan, D.J. Moet, D.C. Hermes, P.W. Blom, R. Andriessen, Large area ITO-free organic solar cells on steel substrate, Org. Electron. 13 (12) (2012) 3310–3314.
[46] S. Lizin, S. Van Passel, E. De Schepper, W. Maes, L. Lutsen, J. Manca, D. Vanderzande, Life cycle analyses of organic photovoltaics: a review, Energy Environ. Sci. 6 (11) (2013) 3136–3149.
[47] A. Facchetti, M. Yoon, T. Marks, Gate dielectrics for organic field-effect transistors: new opportunities for organic electronics, Adv. Mater. 17 (14) (2005) 1705–1725.
[48] F. Krebs, H. Spanggard, T. Kjær, M. Biancardo, J. Alstrup, Large area plastic solar cell modules, Mater. Sci. Eng.: B 138 (2) (2007) 106–111.
[49] R. Rösch, F. Krebs, D. Tanenbaum, H. Hoppe, Quality control of roll-to-roll processed polymer solar modules by complementary imaging methods, Sol. Energy Mater. Sol. Cells 97 (2) (2012) 176–180.
[50] A. Lange, M. Wegener, C. Boeffel, B. Fischer, A. Wedel, The influence of the solvent system, anode conductivity and anode transparency on the performance of printed organic solar cells arrays, in: Lope-C, 2010, pp. 95–98.
[51] A. Knobloch, A. Manuelli, A. Bernds, W. Clemens, Fully printed integrated circuits from solution processable polymers, J. Appl. Phys. 96 (4) (2004) 2286–2291.
[52] K. Hilsenbeck, Optimierungsmodelle in der Halbleiterproduktionstechnik, Ph.D. Thesis, TU München, 2005.
[53] C. Lee, A. Johnson, A decomposition of productivity change in the semiconductor manufacturing industry, Int. J. Prod. Res. 49 (16) (2011) 4761–4785.
[54] N. Kumar, K. Kennedy, K. Gildersleeve, R. Abelson, C. Mastrangelo, D. Montgomery, A review of yield modelling techniques for semiconductor manufacturing, Int. J. Prod. Res. 44 (23) (2006) 5019–5036.
[55] B. El-Kareh, A. Ghatalia, A. Satya, Yield management in microelectronic manufacturing, in: Electronic Components and Technology Conference, IEEE, 1995, pp. 58–63.
[56] J. Kalowekamo, E. Baker, Estimating the manufacturing cost of purely organic solar cells, Sol. Energy 83 (8) (2009) 1224–1231.
[57] M. Hambsch, K. Reuter, M. Stanel, G. Schmidt, H. Kempa, U. Fügmann, U. Hahn, A. Hübler, Uniformity of fully gravure printed organic field-effect transistors, Mater. Sci. Eng.: B 170 (1) (2010) 93–98.
[58] S. Dhople, A. Davoudi, P. Chapman, A. Domínguez-García, Integrating photovoltaic inverter reliability into energy yield estimation with Markov models, in: 12th Workshop on Control and Modeling for Power Electronics (COMPEL), IEEE, 2010, pp. 1–5.
[59] C. Brabec, Organic photovoltaics – technology and market, Sol. Energy Mater. Sol. Cells 83 (2) (2004) 273–292.
[60] A. Risteska, K. Myny, S. Steudel, M. Nakamura, D. Knipp, Scaling limits of organic digital circuits, Org. Electron. 15 (2) (2014) 461–469.
[61] M. Hallgren, J. Olhager, Flexibility configurations: empirical analysis of volume and product mix flexibility, Omega 37 (4) (2009) 746–756.
[62] D. Hwang, C. Fuentes-Hernandez, J. Kim, W. Potscavage Jr., B. Kippelen, Flexible and stable solution-processed organic field-effect transistors, Org. Electron. 12 (7) (2011) 1108–1113.
[63] J. Willmann, Innovationen in der druckbaren Elektronik: Von der Idee zur Produktion. Eine technische und wirtschaftliche Analyse, Dr. Hut, 2013. Available from: <http://tuprints.ulb.tu-darmstadt.de/3644>.
[64] G. Han, M. Dong, X. Shao, Yield management with downward substitution and uncertainty demand in semiconductor manufacturing, Int. J. Prod. Res. 50 (3) (2012) 743–756.