1. - Publishable summary

The ultimate goal of the APPLE project is ***to develop the next generation of sustainable paper-based products*** with specific autonomous functionalities aiming at interacting with their users and/or reporting changes in their environment. A major focus is placed on ***the development of flexible manufacturing concepts based on printing technology*** to produce large area hybrid organic/inorganic papers with improved performance at competitive cost.

To this aim, the APPLE project is focused on 1) the integration of recent advances in functional materials (paper, fibres, inks) and functional components (battery, sensors, display, memory) and their production process upscale and 2) the development of innovative, flexible and cost-effective manufacturing processes based on printing and embedding techniques for the integration of all these functional components on the paper substrate.

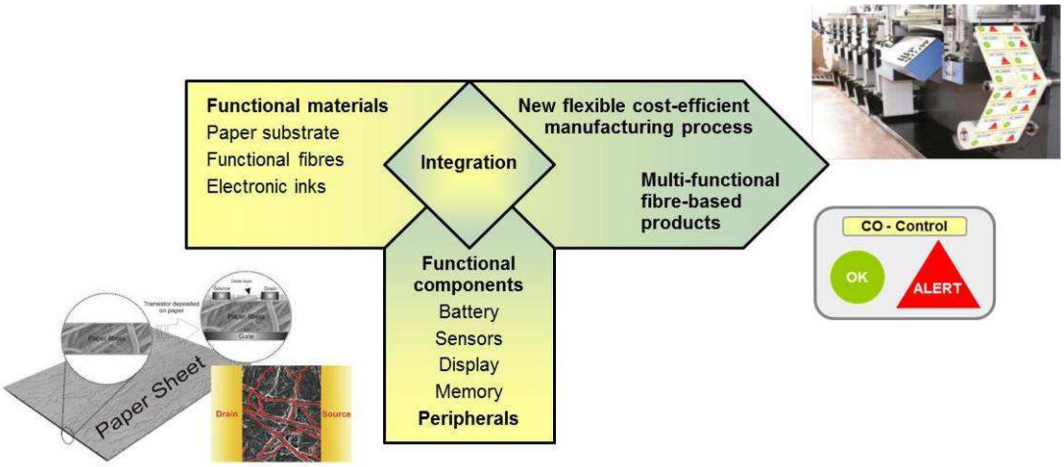

Figure: Concept of the APPLE project

APPLE project requires a multidisciplinary approach, involving 12 research and industry partners with different backgrounds, going from materials science and engineering, to chemistry, physics, electronics and micro/nano-technologies.

Table: Partners involved in APPLE

5 SMEs		IN-CORE Systèmes	LabelTech	polypore	RG Plastiques GROUPE G·PACK
2 Industries		Felix Schoeller Group Best Performing Papers. Worldwide.		VARTA THE BATTERY EXPERTS	
4 Institutes 1 University	ctp centre technique du papier	cea	TNO	VTT	UNINOVA CEMOP FCT FACULDADE DE CIÊNCIAS E TECNOLOGIA UNIVERSIDADE NOVA DE LISBOA

The 4 main technical objectives within the period focus the development of the demonstrators 1and 2 of A3Ple project. This leads to:

- Develop new functional materials at industrial relevant scale (paper, fibres and inks)
- Develop printable functional components at industrial relevant scale
- Optimise design integration and develop a new manufacturing process

Work performed within the 30 month period (until M30)

WP1. Final versions for *(1)* End-user and technical specifications and *(2)* materials and components specifications are completed for the three targeted demonstrators.
Methodologies for testing LCA, recycling, environmental and reject issues of materials, components and demonstrators were defined. LCA was performed to compare FS paper to FR4 (Plastic for conventional electronic): CO2 impact factor is 1000 lower for paper.
An inquiry whose objective is to define the potential market development, is ready. The interviews with future potential end-users will start very soon.

WP2. Three reference papers were selected, their printability in relation to the functional and peripheral components were tested. At M18, requested properties converge into one reference paper (170 g/m²) that needs to be upgraded in order to decrease the thickness and consequently increase runability at industrial scale. Because this paper is produced with different kind of coating layers, the basis weight cannot decrease below 150 g/m². Five polymers have been selected to substitute the PE coating and tested at laboratory scale. Biodegradability and eco-toxicity tests are performed on the selected paper.

The study of the paper properties on the transistor behaviour has started; 2 kinds of papers appeared rather suitable for transistor and memory components. Use of MFC (MicroFibrillated Cellulose) seems to be promising for memory.
Flexographic silver ink is validated as conductive ink. For the display, the transparent conductive ink was tested in WP3.

WP3

Battery. Two routes for making the batteries were defined: the VaP route and the CoR route. The last one requires a colamination/removal on R2R equipment (not planned in the DoW). Besides, one step concerning the implementation of the separator was identified as highly risky while the electrolyte filling step could not be undertaken, because it needs anhydrous atmosphere, not available at the printer. Consequently, this route was definitively abandoned. The VaP route's feasibility could be only demonstrated at the lab scale. The best sample of battery obtained according to this route is a TFB with the overall area of 62x50 mm² and a maximum thickness of 400µm. The battery performances are an initial capacity of about 35mAh for a nominal voltage of 3.2V. The lifetime needs to be improved and the manufacturing needs to be made reliable.
The hybridization will start on commercial Enfucel battery that requests the same electrical connection on the label as the battery developed in the frame of A3Ple.

Sensors.The development of CO sensor based on CNT (Carbon NanoTube) has started on a water base ink formulation. First prototype on FS papers has already been done at lab scale with spray technique. The sensor is not suitable for detecting CO variation. The development of such a CO sensor must be stopped. The possibility of measuring NO_2 thanks to CNT will be evaluated.
The H_2S sensor is developed according to literature published (Crowley and all). Investigations focus on *i)* decreasing the sensitivity of the measure towards the moisture and *ii)* improving the sensor behaviour in relation with the paper surface properties. Further investigation showed that polyanyline can be removed without any negative effects on the sensor efficiency.
The first design of temperature sensor has been tested at lab and industrial scale but the performances were not good enough. Active particles have been synthetized for increasing the ink performances. The flexo printability of this ink is being improved.

Display. A fully printed EC display on paper for DEMO1 and DEMO2 has been developed in a lab-scale. One part of the display is printed directly on paper by flexo printing. The second part (WO3 and electrolyte) is printed on PET/ITO film. Then the two parts are laminated. The mechanical stability of the display (flexibility) and electrical cycling are still to be improved. First prototypes have been demonstrated at M30. There are no major obstacles in development of this component, and its application in A3Ple demonstrators. Tests have been performed to replace ITO by transparent conductive ink without success.

WP4
Active components.
The strategy selected for transistor is based on electrolyte gated devices (EGFETs). After showing in M24 that the EGFTEs can be produced using PVD and spin coated nanoparticles zinc oxide thin films, the challenge is now on depositing the semiconductor layer by printing techniques.

Passive components.
Resistors values range has been defined and printed using flexographic water base inks, at laboratory and industrial scales. Resistors with target value were introduced with success on demo 1's and demo 2's printing circuits.

Interconnections based on bridges have been developed successfully at lab-scale via screen-printing. Lab-scale and industrial flexo printing trials give poor results. Recommendation is to use the screen printing.
Capacitors have been realised at lab-scale using the same layers as for the bridges.

WP5. The electrical circuit based on electrical behaviour of each printed component has been built for demo1 and demo2. Connections, resistors and component pads were printed at industrial scale. Then a hybrid circuit was made with this and Si based sensor, transistor and display. The **hybrid-Demo1-V1 and V2** and the **hybrid-DEMO2-V2** work as expected proving both printing and electrical integration efficiency! Replacement of conventional components by printed ones will induce modifications in the electrical design of Demo2.

WP6. 8 industrial printing test runs were achieved at LT factory in order to transfer the results of the previous WP. A first visual inspection system was planned, manufactured by ICS and installed at LT.

WP8. A public webpage www.A3Ple.com has been created. The hybrid-Demo 1 was presented at OE-A competition organized on LOPE-C 2013 in München (fig below).

Figure: A3Ple hybrid demo1 on OE-A booth at LOPE-C exhibition.